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AIRCRAFT RESEARCH AND TECHNOLOGY
FOR
ANTIMISTING KEROSENE CONFERENCE
FEBRUARY 18 – 19, 1981
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CONFERENCE PROCEEDINGS

JUNE 1981

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
TECHNICAL CENTER
Atlantic City Airport, N.J. 08405

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WELCOMING ADDRESS

By

JOSEPH M. DEL BALZO

DIRECTOR, FAA TECHNICAL CENTER

I welcome you to the Technical Center. We represent the Federal Aviation Administration's (FAA's) hands-on capability to do engineering work. This is the only place you will find a laboratory that belongs to FAA and supports what the agency does in the field of aviation safety.

We don't make the regulations rather, our mission is provide the technical data to support many of the things that FAA does in terms of certification and regulation. And we do this scientifically and objectively.

Let me welcome you also to the first public antimisting fuel conference. I am not going to waste any time now telling you what antimisting fuel is or what it does. The fact that you are here is an indication that you have some understanding of the subject we are going to be talking about for 2 days. Let me just say that we have been working on the problem of aircraft cabin fire safety for several years. Our research includes work not just on antimisting kerosene, but it includes work on better cabin interior materials, evacuation slides, and emergency lighting. That is a pretty important "shopping list". I think you all know that of all the items we are working on, the FAA's special aviation, fire and explosion reduction advisory committee (SAFER) noted that fully developing the antimisting kerosene (AMK) technology could prove to be the single, most significant safety improvement to reduce the post-crash fire hazard.

We have worked with the Royal Aircraft Establishment (RAE) of the United Kingdom (UK) and we've worked very closely with the National Aeronautics and Space Administration (NASA) which has done much of the basic research and provided a lot of technology support to the program. As a result, we believe that an antimisting additive is technically feasible and it can provide increased protection against the post-crash fuel mist fire. After 2 years of testing — and you will hear more about this during these 2 days — we have not uncovered a problem that we believe to be technically unsolvable. We do have concerns, however, that still have to be satisfied. But we've done a lot, we've learned a lot. There's still a lot more to do.

Some of our concerns are technical and they include the fuel's compatibility with the engine, aircraft and airport handling systems as well as problems associated with blending, degrading, and storage.

Our main concern today is cost. What is it going to cost to produce the additive in large quantities. What are the costs associated with quality control, engine modifications, and a number of other things we will be talking about in these 2 days.

I think it is too early to judge how much it is going to cost. However, work has begun to let us better understand the total cost of introducing the additive into operation and to better understand the safety payoffs of the introduction of the safer fuel.

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We will hear more about this work later this afternoon. Before I close let me make a couple of final points. The work that we have done has been done cooperatively. We've done it with not just parts of FAA, but the UK, NASA, and a substantial amount of industry participation. Normally when an FAA person stands up someone asks him this question: "What is cooperation like between us and NASA? Isn't there a lot of duplication?" The answer is "certainly not." "We cooperate, there is no overlap." If you were to ask someone from NASA the same question now, you would get the same answers. I think if you had gone back and asked those questions 3 years ago, you would have received those answers but I don't think it would have meant anything at all. Today, when you ask the question about FAA and NASA participation the answer is real and the AMK Program is one of the best examples that I can think of, where FAA and NASA contribute the part of the technology that each can do best. There are things we do very well, there are things that NASA does very well. What we have managed to accomplish in this program is getting the best from both organizations, all focusing on an important problem. That is not meant to be a sales pitch, but it is just something I thought you would appreciate for it is true.

A second point is that while we do need a better understanding of costs, we need to know those costs as they finally relate to the safety benefits. Point 3, and this is something you are going to hear in the keynote address by Walt Luffsey, there is an FAA commitment to see this program through to successful completion on schedule. Point 4, and I can't make this one strongly enough, the time has come now, today, to share with you the results of our 2 years of work, to tell you what it is we think we know, to tell you what it is we think we don't know and to encourage your participation during the remainder of the program.

We strongly encourage your active participation during this conference; give us the benefit of your comments, both the positive ones, as well as the negative ones. Where you think we're all wet, tell us. Where you think we are on the right track, tell us that, too. I said at the beginning that this is the first public antimisting fuels conference and the reason I said the first, is that there is likely to be others along the way as we reach major milestones in the program. It's important for us to stay in touch with industry and the aviation community so all will know where it is we are at any given moment in time and where we are going.

I would expect a second conference to occur soon after we award a major contract to develop other anti-misting additives. You will be hearing a lot about this during these 2 days. That conference could occur sometime late this year or early next. I think that is the next significant milestone in the program.

So with that, again I welcome you and I hope you'll agree that the next 2 days will be productive both for you and for aviation safety.

Thank you.

KEYNOTE ADDRESS

By

WALTER S. LUFFSEY

ASSOCIATE ADMINISTRATOR FOR AVIATION SAFETY, FAA

Good morning, welcome to the first conference on AMK. As Associate Administrator for Aviation Standards, I am responsible for airworthiness, operations, safety, security, and the aeromedical aspects of the FAA's responsibilities. I know that the aircraft manufacturers and airlines produce and operate the safest system for transporting people. However, impact-survivable accidents have occurred during approach, landing, and takeoff where fuel was released from severed wings or damaged fuel tanks, resulting in external fires and thermal fatalities. The fuel released under such conditions forms a fine mist of combustible vapor which is readily ignited, resulting in fire which could envelope the aircraft and serve as a major ignition source for continuing fuel spillage as the aircraft comes to rest.

Fuel was released from separated wings in 17 impact-survivable United States (U.S.) air carrier turbine aircraft fatal accidents from 1964 through 1976. Since antimisting fuel is intended to inhibit ignition and flame propagation when fuel is released during wing separation and tank damage accidents, it is possible to speculate, based upon these accident experiences, that up to 32 percent of the fatalities in impact-survivable accidents might have been prevented by the use of antimisting fuel.

The availability of a practical additive that would produce an antimisting kerosene, which, when released from a ruptured fuel tank would preclude the formation of a fireball, would save many lives. Such fuel must provide protection throughout a broad range of operating regimes — from a few minutes after fueling through takeoff to the end of a light. However, such a modified fuel must still be compatible with the aircraft fuel system and engine with minimum or no aircraft changes to be considered practical.

The Imperial Chemical Industries, Ltd (ICI) company in England, supported by government research funds, has spent over 10 years developing such an additive, known as FM-9. The British conducted a series of rocket sled tests to evaluate various concentration levels of FM-9 to establish adequate protection at selected velocities. Also, large-scale tests were conducted using a mock-wing spillage facility at various concentrations of fuel using FM-9 to determine needed concentration to preclude fuel ignition. The results of both of these tests were very encouraging. The performance of "jet A" fuel FM-9 was so promising that it could not be ignored. A Memorandum of Understanding (MOU) between FAA and the British was signed in June 1978, outlining a 2-year effort by the British, NASA, and the FAA. This memorandum assigned specific tasks to each party with a goal that within a 2-year period, sufficient data would be available to determine if such a modified fuel was feasible. Many facilities and much talent was assigned to evaluating FM-9: Southwest Research Institute, Jet Propulsion Laboratories, NASA Lewis, Pratt and Whitney, and the FAA, to name a few. ICI Americas began supporting the program during this period. In England, the RAE and ICI Ltd accomplished their assigned tasks.

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The following objectives were addressed during the 2-year effort:

1. Assess the fire resistance capability of AMK under representative crash conditions.

2. Develop a suitable method for degrading the AMK between the fuel tank and the engine to reduce compatibility problems.

3. Develop a means of measuring AMK characteristics prior to departure to assure the fuel is at a proper concentration.

4. Demonstrate the feasibility of blending FM-9 with kerosene at the aircraft fueling point.

5. Determine if AMK has a greater affinity for water than jet A.

6. Test current engine components using AMK to establish what operating problems exist and possible solutions.

During this 2-year period, the composition of FM-9 was somewhat altered to ease the blending process of the additive into jet A. A carrier fluid was added that resulted in 0.3 percent FM-9 and approximately 0.6 percent fluid. This mixture of nearly 1 percent, resulted in a much higher fuel displacement than desired.

The U.S./UK management meeting in November 1980 reviewed all results of the past 2 years research using FM-9 and considered the recommendations of the technical committee. There were some problems with FM-9, which you will hear about in detail in the individual presentations, but there was no overwhelming fault that would warrant stopping the program. The management group also endorsed the FAA's Engineering and Development Program Plan on Antimisting Fuel, dated September 1980, that calls for all research necessary to support a notice of proposed rulemaking to be completed by mid-1984. FM-9 will be utilized in this phase of the program to define the feasibility of the use of antimisting kerosene and to outline the scope of efforts needed to carry through to a recommendation for introduction of the fuel into civil aviation use.

The intent of this work is to establish a series of procedures, techniques, and equipments to investigate the properties of the FM-9 fuel. Additionally, the necessary screening tools and technology to assess the acceptability of other candidate antimisting fuels are expected to emerge from the work.

Laboratory-scale flammability tests will be established using documented techniques, procedures, and equipment that will allow reliable examination of antimisting fuels.

The possibility that small quantities of degraded antimisting fuel may be present in a crash instance must be investigated. Such degraded fuel could be released from components of the engine, which would increase the fire risk. Examination of the basic rheology of the fuel will occur through a series of efforts to establish what problems may exist in setting quality control for a uniform product.

There is concern that the heat transfer characteristics may not be sufficient to perform one of the other major functions of the fuel; that is, the extraction of heat from the lubricating oil. A new function must be introduced into the engine

fuel system — that of intentional degradation. Such techniques and equipment must be power efficient and lightweight. Efforts to examine methods of intentional shearing or degrading of the fuel to produce acceptable engine cycle operation will be conducted.

The antimisting fuel normally requires a period of stabilization for the full benefit in antimisting flammability control to develop. Obviously, if bulk blending techniques are applied to the blending of the fuel at the delivery point to the aircraft, this time requirement might not be met. Examination of the techniques will be made to assure that the desired characteristics are achieved, considering time factors and possible blending location.

Use of aircraft fuel system simulators and engine bench testing of components will be employed to identify critical operational problem areas associated with the use of the antimisting fuel.

Projects to address the factors that affect the quality of the resultant antimisting fuel as a result of the blending process will also be addressed. These include blending location such as the refinery, airport tankage system, aircraft in-line, blending technique, production rate potential, and variations resulting from the use of alternate base fuels. The implementation will be strongly influenced by the benefit/cost aspects of the modified fuels usage.

The three parts to this program are the ground and flight test, the full-scale aircraft crash test, and the establishment of the final benefit/cost comparison.

The first major test effort in this final part of the overall development program is the conduct of ground and flight testing with the candidate fuel. As a precautionary measure, conventional fuel will also always be onboard. The ground and flight test aircraft will have one engine and associated support system dedicated to the antimisting fuel.

The culmination of the development test work is the full-scale crash demonstration of an aircraft filled with the antimisting fuel. It is proposed that the crash vehicle be impacted into a preselected site that would supply the appropriate ignition exposure to show acceptability of the fuel characteristics.

The principal purpose of our meeting today and tomorrow is to clearly explain what safety benefits AMK can provide, the problem areas, and possible changes needed to use such a fuel. The second motive behind this conference is our desire to hear from anyone as to alternatives, criticism of our approach, or other comments, as appropriate. Basically, at this stage, we need the thoughts of the people that would most directly be affected by the use of modified jet A.

There may be additional meetings in the future as significant milestones are reached, to inform all interested parties of the progress in developing this fuel into a viable product for everyday use in turbine-powered aircraft.

Again, I want to thank each of you for your interest in aviation safety.

ANTIMISTING FUEL ENGINEERING AND DEVELOPMENT PROGRAM

By

W. T. WESTFIELD

A general overview of the important parts of the Antimisting Fuel Program, as structured by the FAA, gives the rationale that the FAA has used to arrive at the program referred to as the Antimisting Fuel Program. This has been a cooperative effort between the United States and the United Kingdom under a MOU signed in June 1978.

The critical issues that formed the basis of work under the MOU in summary are; first, can the fuel be produced in available quantities with the proper quality controls that are necessary and can it be made at a cost that is reasonable? Secondly, is the degree of flammablity resistance provided at landing or takeoff speed sufficient to preclude the possibility of a fireball? Thirdly, are there aircraft, aircraft engine, or airport fuel system modifications that are necessary to allow the use of this fuel? Lastly, can blending of the fuel to a form which is useful to the aircraft and degrading of the fuel for use in the engine be accomplished considering the logistics of an operational system?

The conclusions of the work under this MOU were that the use of antimisting fuel in the form of FM-9 and in the concentration of nominally 0.3 percent by weight, does give the promise of significant fire protection in post-crash situations where a fireball could exist. The second major conclusion was that although there are problems, no insurmountable technical problems are envisioned at this time. There are areas of concern which represent a significant amount of work that has to be accomplished during the next couple of years. These specific problems are addressed in the program.

Relative to the increased cost using the additives, it is generally agreed that there is commercial incentive to produce the additive. Coupled with industrial competition, this incentive should result eventually in the lowest possible cost factor. It is realized, however, that the increased cost is a problem that is real. Additional production facilities and handling equipment which appear to be necessary are likely to be amortized over the life of the use of the fuel.

Work has shown that stringent care must be taken to assure the quality control of not only the polymer but the individual monomers that make up the polymer and the processing that is done to produce the final product. Over and above that, the introduction of the polymer additive to the fuel itself represents an area where increased quality control is necessary. Naturally, increased quality control problems result in an increased cost.

The third item of concern is handling and fueling. It has been a major thrust throughout the initial program to use a system that blends the additive into the fuel at the point it enters the aircraft. A degree of difficulty has been experienced in achieving this to date, and specific efforts are identified in the program relative to this problem. Regardless, the question of preparation of fuel at the refinery and storage at the airport has not been discarded.

The last of production concerns are the restrictions that are seen in trying to blend at low fuel ambient temperatures or with fuel of low aromatic content.

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There are concerns, also, with the rheological properties of the fuel or flowing conditions of the fuel. At this time, it appears that degradation of the fuel to break the long chain polymers into smaller parts will be a requirement. The main effort to date, has been toward the mechanical degradation of these polymers. Chemical degradation has been shown to be possible and rapid, although costly and complex. One item that should be added at this point is in the event turbine engine power management technology drives toward electronic fuel controls, the level of degradation that is presently necessary may be relaxed. Gellation is listed as a concern. Formation of gel has occurred on the discharge side of filters and on pump housings. Whether the level of gellation presently seen will increase or will stabilize is as yet an unknown. It is not a normal defined process, so it does represent a concern and is, therefore, a part of the research program.

The last item, equilibration, is probably the most serious concern in the rheological area. Of necessity, most of the work that has been done to date has been done on fuel which was prepared at the manufacturers plant or in a batch process by the various researchers; therefore, the fuel has had time to stabilize and equilibrate before it was tested. When a system of in-line blending is used, the fuel does exhibit a changing characteristic. This changing characteristic is best described in the power that is needed to degrade the fuel. Significant differences in power required are noted if degradation is attempted immediately after in-line blending of the fuel. The level of power requirement decreases with time, and within 2 to 24 hours the fuel has become stable at its normal level. However, the 2 to 24 hours time is unacceptable for an operating environment and work is needed to clarify this situation.

There are concerns in the compatibility area. Degradation of the fuel necessary for current engine systems to operate properly requires modification of the fuel pump, or an additional device to degrade the fuel. Such a mechanical degrader is expected to consume approximately 1/2 percent of the thrust specific fuel consumption of the engine.

One of the driving factors in the requirement for degradation is the filter sizes presently used in controls and systems. The 10 micron metal filters used in controls cause gellation problems. Forty micron paper filters, which in reality are not uniform filters, are also a source of difficulty.

It has been shown that jet transfer pumps of aircraft systems do not function efficiently on the antimisting fuel.

The last concern is the area where the least information is known: the area of combustor performance. Present day fuel nozzles have been designed to produce efficient combustion above 99 percent in most cases, but have been designed to operate using a fuel of a certain viscosity and consistency. The antimisting fuel, by its very design, produces spray patterns which clearly show an area where additional work must be accomplished. However, the technology of combustion systems developed in recent years has vastly improved such that while there is concern, it is felt that the problems are solvable.

These concerns have been used in the development of the overall antimisting fuel program. Figure 1-1 lists the separate individual phase titles that comprise the program. Phase I is identified as a feasibility and FM-9 development phase.

The statement of feasibility was issued by the Management Committee under the MOU November 1980. It was agreed that the MOU should continue in effect toward the solution of FM-9 problems to a point where demonstration of its use in an operating system could be made. The second phase of the work is identified as full-scale validations and consists of two main items, ground and flight test of the fuel in an operating system, and the full-scale crash of an aircraft representative of operational use while fueled with the antimisting fuel.

Phase IIA is identified as an alternate, or candidate fuels effort. Success in phases I and all parts of phase II on the FM-9 fuel would lead to a mid-1984 data base which would be supportive of a regulatory recommendation to be made by the Technical Center to the regulatory side of the agency as indicated in figure 1-2. If the data base is sufficiently strong, action could be initiated to require use of such fuel. Phase IIA is shown as part of the overall investigation in the event that technical problems arise with the FM-9 fuel that cannot be solved. It is the intent to investigate alternate candidate fuels which can compete with the FM-9 fuel such that a maximum effort can be derived from the use of the funding. In the event that phase IIA produces a fuel which is superior to FM-9, completion of the data base listed for mid-1984 would be delayed for approximately 1 year. But that delay would occur only if a fuel was shown to be vastly superior or that FM-9 was improper and a different fuel could do the job. This decision point rests in early fiscal year (FY) 1983. In the event that a definitive statement cannot be made at that time, concerning either FM-9 or another fuel, the intent is to terminate this research and development program.

Figure 1-3 shows the schedule for phase I. Assuming continued satisfactory performance of the FM-9 fuel, its laboratory and scale problem solving would be completed in early 1983. Work is continuing in each of the listed areas to satisfy the concerns identified earlier. As can be seen in figure 1-2, the intent is to reach solutions to these problems in time for the early FY-1983 preparation of the full-scale validation tests. Ground and flight test preparation as well as crash test preparation is underway in FY-1981 in order to conduct the crash test approximately 1 year after completion of the problem solving with FM-9. If FM-9 gets in trouble, a switch to a phase IIA fuel, if available, would occur. The crash test would then occur approximately a year later. Naturally, if the crash test is delayed a year, the data base completion would also be delayed.

The phase II full-scale validations will be discussed separately. The first is the B-727 ground and flight test, the schedule for which is shown on figure 1-4. The fuel system of the agency B-727 at the Technical Center will be modified by late this fiscal year. Instrumentation of the fuel system will be underway to gather maximum information. The flight test plan is in preparation and will continue to be revised and upgraded as additional information about the development of the fuel is obtained. Operational ground testing should begin late in FY-1982 and be completed in early FY-1983. The types of work included in the flight test are shown in figures 1-5 and 1-6. The actual flight test of the system will last about a year, to collect approximately 50 hours of actual flight test data. Parallel to the flight test itself will be systems modifications. As the flight test progresses and information is collected, there most likely will be a need for some change of systems or possibly deletion of some changes that were initially incorporated. The final item is analysis of the flight test data for inclusion in the data base of mid-1984.

The other major piece of work in phase II validations is the full-scale transport crash test. Figure 1-7 shows the planning and direction which this effort is taking. The NASA and Department of Navy organizations are being utilized to supply expertise from Dryden Flight Research Center and the Naval Weapons Center in the actual conduct of the crash itself. The intent is to have the aircraft modified for remote control so that a true crash can be conducted. Details of the actual flight approach to the crash such as the speeds and other conditions will result from ongoing contracts with Douglas, Lockheed, and Boeing aircraft to analyze past crashes and produce suitable crash scenarios that describe survivable crashes. Conduct of the necessary pre-crash ground and flight operating test of this aircraft will begin in mid-FY 1983 with the conduct of the actual crash test in mid to late 1984. Post-crash data anlaysis will be completed in early 1985.

Because of the significance of this crash, it is not to be exclusively an antimisting fuel test. Other equipments that will supply information of need to the FAA will also be onboard. Figure 1-8 shows a partial list of the type of equipment to be incorporated into the aircraft prior to the crash. Item 1, the development of the crash scenario is being developed for FAA, as mentioned previously. The second and third items on the list are specifically related to the antimisting fuel. The next four items address the structural or crashworthiness aspects of the test. Structural dynamics instrumentation will collect data to support computer modeling of the crash instance. Advanced seats and restraint concepts will be onboard. Floor palletization, overhead, and galley concepts will also be incorporated as well as emergency exit concepts.

The last three items that are on the list of figure 1-8 address the cabin fire safety approach to a survivable crash in the event that the antimisting fuel fails. Seat, wall panel, flight recorder response information, and advanced extinguisher concepts are among those to be examined.

The B720 crash program is not solely for the purpose of the antimisting fuel development nor is it solely to evaluate FAA developments. Included in this crash will be crashwortniness equipment, cabin fire safety equipment as developed by various other Government and industry organizations around the country. While the program is primarily directed and coordinated by the FAA as far as goals are concerned, NASA is a major element in the planning and will have responsibility for actual preparation and instrumentation of the aircraft, as well as the successful crash.

The program described to this point assumes that the FM-9 fuel performs as expected and that no development problems occur which indicate that they cannot be solved. However, phase IIA has been identified as a candidate fuels evaluation phase. This phase is currently underway with the goal in mind of developing alternative additives to the FM-9 fuel in the event that problems develop with FM-9 that cannot be overcome. Secondarily, the investigation into alternates may produce a fuel which in itself is superior to the FM-9. In short, it represents the industrial competition which will foster incentive.

FM-9 has given the FAA several items. It has demonstrated the feasibility of the concept in that no problems of unsolvable nature have been overturned. Secondly, it has developed the research, development, and evaluation tools that are needed to assess whether any fuel can produce the same results, and lastly, it has, in a general manner, identified the major problem areas within the concept of antimisting fuel, and where developmental and reliability engineering is necessary.

The FAA has issued a solicitation for industry to respond to, and produce fuels which can demonstrate equal or better flammability protection and handling qualities as that afforded by FM-9. This solicitation is also designed to produce a fuel such that minimal changes would be required to engine, aircraft, or airport fuel systems. Lastly, it must blend readily or be compatible with current specification aviation kerosene. The solicitation uses as an approach a prescreening phase prior to award of contract. During this prescreening phase, data will be solicited concerning the fuels performance. If that data indicate it is necessary, samples of the fuel will be requested to demonstrate that the fuel does meet the stated objectives, and secondarily, to identify if potential problems exist. After award, the tailoring of these fuels to minimize the problems and to improve the fire resistance of the fuel will be pursued.

An important point must be made. The FM-9 formulation has been frozen for the past 2 years while the feasibility was being determined. It is not the intent of the FAA to develop a manufacturers fuel but rather to encourage development of fuels that are better than FM-9. The schedule calls for a response date for the prescreening information such as the data and the samples of June 1981. Award is planned for September 1981. Between the award date and August 1982, problem solving and defining of the fire resistance of the fuels that meet our initial requirements will be underway.

It is possible that multiple awards will be made. Industry or any other organization which responds to the solicitation will be requested to contribute funds in addition to the FAA funds. The multiple award facet of this solicitation will be kept to a minimum to assure only the most promising is investigated by FAA.

Lastly, if no solicitation responses are received. The FAA intends to continue the program using the FM-9. Research will be conducted to improve its characteristics and if successful, the regulatory recommendation data base referenced early in this program discussion will address the use of fuel of FM-9 character.

The FAA program in antimisting fuel as conducted by the Technical Center may reach a point where FM-9 or no other alternate fuel appears to have sufficient promise, in that event, the FAA will terminate this program.

PHASE I: FEASIBILITY/FM-9 DEVELOPMENT

PHASE II: FULL-SCALE VALIDATION -GROUND/FLIGHT TEST-CRASH TEST

PHASE IIA: CANDIDATE FUELS EVALUATION

FIGURE 1-1. ANTIMISTING FUEL PROGRAM PHASES

FY-79 FY-80 FY-81 FY-82 FY-83 FY-84 FY-85

PHASE I.
FEASIBILITY/FM-9 DEVELOPMENT

PHASE II.
FULL-SCALE VALIDATION

-GROUND/FLIGHT TEST

- CRASH TEST

PHASE IIA.
CANDIDATE FUELS EVALUATION

REGULATORY RECOMMENDATION
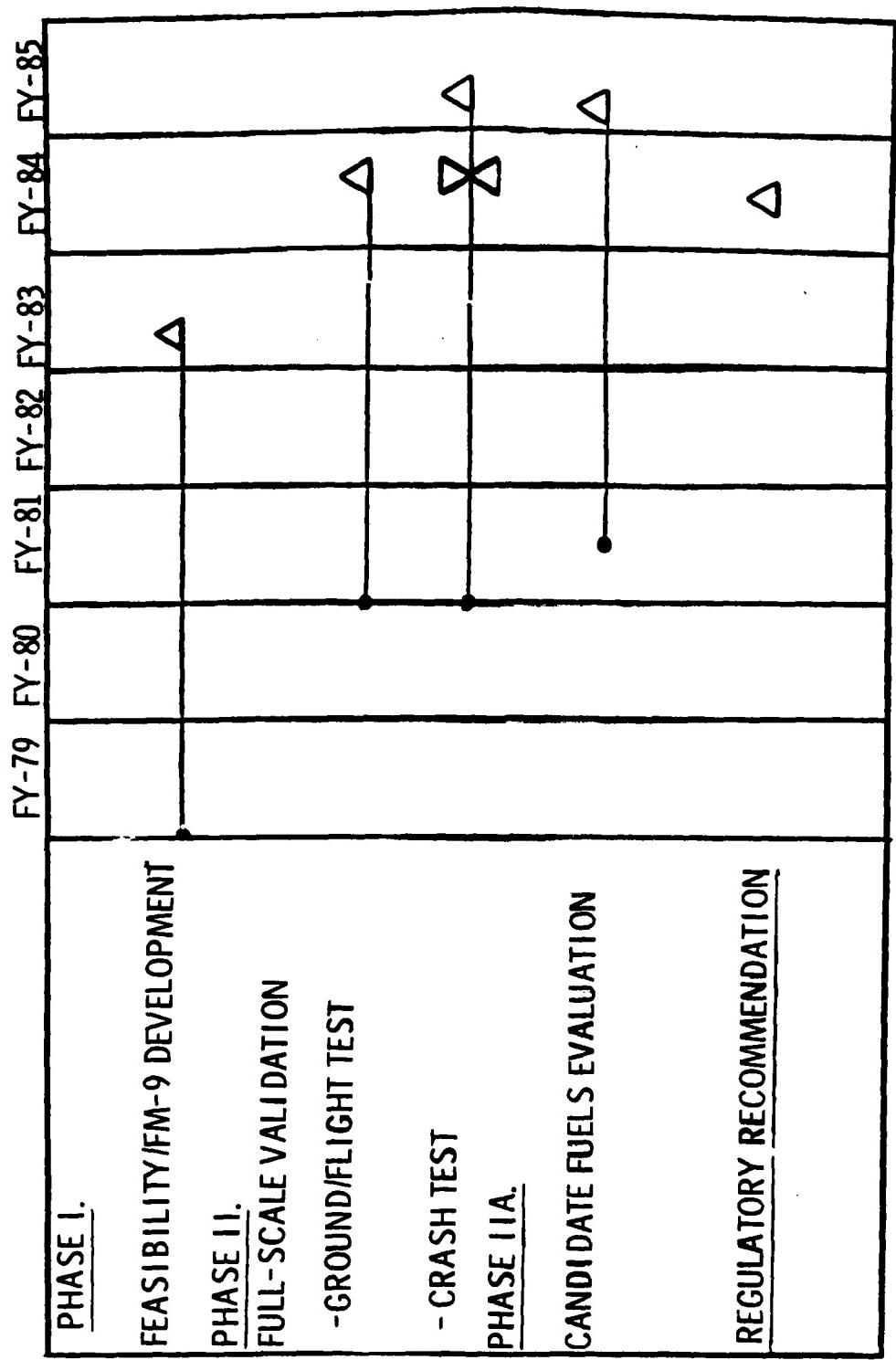
FIGURE 1-2.   OVERALL ANTIMISTING FUEL PROGRAM

1-7
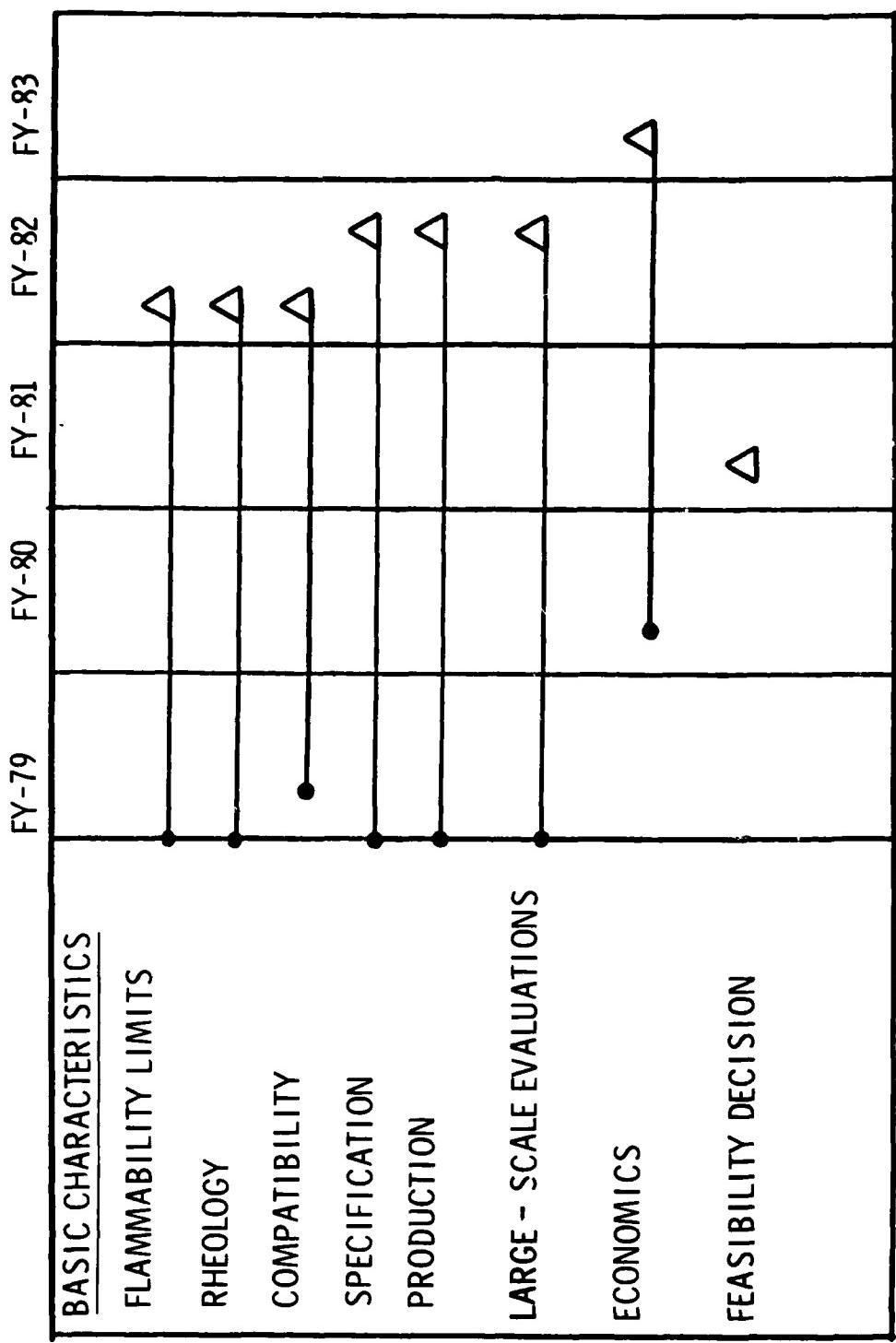
FIGURE 1-3. PHASE I — FEASIBILITY/FM-9 DEVELOPMENT ANTIMISTING FUEL PROGRAM
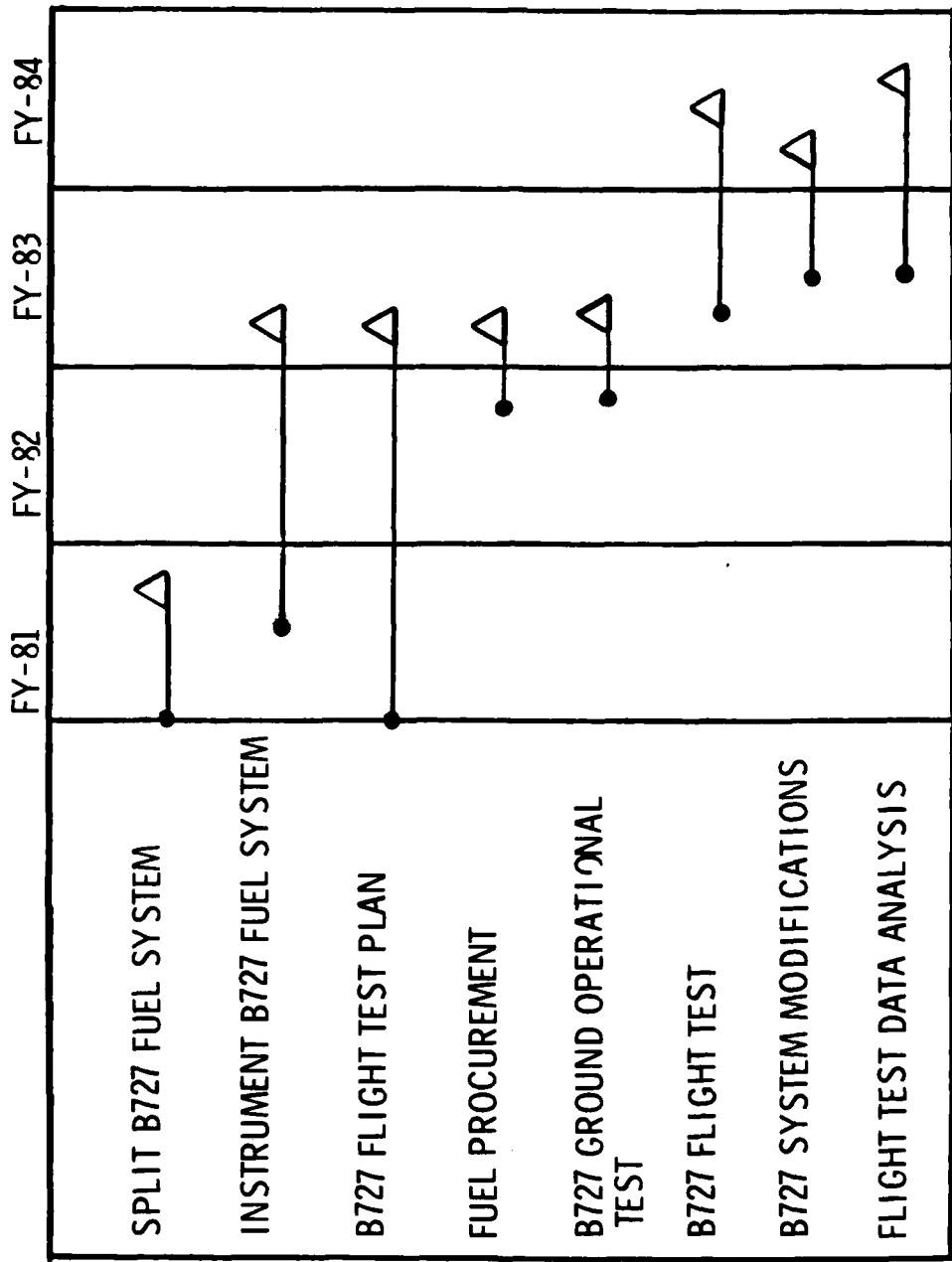
FIGURE 1-4. PHASE II — FULL-SCALE VALIDATION B-727 FLIGHT TEST W/FM-9

FUEL HANDLING CHARACTERISTICS

ENGINE START

ENGINE TRANSIENT EFFECTS

TAXI

AIRCRAFT ACCEL/DECEL (HIGH SPEED TAXI)

ENGINE SHUTDOWN PROCEDURE

FIGURE 1-5.   B-727-30 GROUND OPERATIONAL TEST

TAKE-OFF/LANDING

CLIMB

CRUISE (HIGH AND LOW SPEED - HIGH AND LOW ALTITUDE)

ACCEL/DECEL

TRANSIENT POWER EFFECTS OF ENGINE

ENGINE PERFORMANCE

    LOW ALTITUDE HIGH TEMPERATURE TAKE-OFF/LANDINGS
    HIGH ALTITUDE COLD TEMPERATURE TAKE-OFF/LANDINGS

MAXIMUM ALTITUDE RELIGHT

RAIN AND THUNDERSTORM EFFECTS

FIGURE 1-6.   B-727-30 FLIGHT OPERATIONAL TEST

Crash Test Plan Schedule (FY-81 through FY-85)

Activity	FY-81	FY-82	FY-83	FY-84	FY-85
CRASH TEST PLAN DEVELOPMENT AND COORDINATION	△		△	△	
AIRCRAFT AT NASA, DFRC	△		△		
AIRCRAFT MOVE TO CRASH SITE			△		
REMOTE FLIGHT CONTROL DESIGN DEVELOPMENT	△		△	△	
AIRCRAFT INSTRUMENTATION DESIGN & INSTALLATION	△		△ △		
AIRCRAFT FUEL SYSTEM MODIFICATIONS			△ △	△	
GROUND & FLIGHT OPERATIONAL TESTS			△	△ △	
CRASH SITE PREP/ INSTRUMENTATION				△	
CRASH TEST				△	
POST CRASH TEST				△	△
CRASH DATA ANALYSIS				△	△

FIGURE 1-7.   FULL-SCALE TRANSPORT CRASH TEST SCHEDULE

1-11

DEVELOP SURVIVABLE CRASH LANDING SCENARIO

ANTIMISTING FUEL FLAMMABILITY PROTECTION

ANTIMISTING FUEL FUNCTIONAL OPERATION IN AN AIRCRAFT FUEL SYSTEM

AIRFRAME STRUCTURAL DYNAMICS ANALYSIS

ADVANCED SEAT/RESTRAINT CONCEPTS

FLOOR PALLETIZATION/OVERHEAD/GALLEY CONCEPTS

EMERGENCY EXIT CONCEPTS

FLIGHT RECORDER RESPONSE/ACCURACY

ADVANCED SEAT/WALL PANEL MATERIALS

ADVANCED EXTINGUISHER CONCEPTS

FIGURE 1-8. FULL-SCALE TRANSPORT CRASH TEST OBJECTIVES

1-12

Questions and answers following "Antimisting Fuel Engineering and Development Program"

Discussions:

Mr. Doherty: Jim Doherty, General Aviation Manufacturer's Association. Does your last statement apply equally to the crash test? In other words, if the material does not develop properly, would or would not the crash test come and under what circumstances?

Mr. Westfield: We would not crash that aircraft for the purpose of the antimisting fuel if the fuel did not develop properly. The aircraft would then be diverted to the other programs I have suggested and those organizations would take over.

Dr. Carhart: Elmer Carhart, Naval Research Laboratory. During your flight testing you did not mention whether or not you were going to take a look at the rheological properties of residual fuel after prolonged flying. Do you intend to do that as part of your flight testing?

Mr. Westfield: A definite part of our program is to monitor the rheological properties of the fuel remaining in the aircraft after testing. We don't have any strong data at this point as to whether there is unwanted degradation of the fuel occurring as a result of a flight, so we will be taking samples periodically.

Mr. Peat, Rolls Royce, Derby, England. Is it your intention to examine just one fuel or several fuel additives?

Mr. Westfield: It would be ideal if one fuel stood head and shoulders above the others. In the event that we have two fuels that are close, it could very well be that you may see an aircraft with two separate fuels.

Unidentified Speaker: Are you considering using reduced flash point kerosene in your program?

Mr. Westfield: Yes, we have a project underway to look at the impact of using reduced flash point kerosene fuels as the base fuels.

Mr. Longjohn: Peter Longjohn. Technology developed in Canada is called explosafe. Will technology be incorporated in the wing tanks?

Mr. Westfield: There is a possibility that type of equipment could be put in for evaluation against the antimisting concept. If we had the time to incorporate it, it would be done.

WING SPILLAGE TEST

By

ROBERT F. SALMON

FAA TECHNICAL CENTER

Good morning. I will be discussing the results of tests conducted at the Technical Center with the Wing Spillage Facility. You have already seen segments of typical tests conducted on the facility and I will briefly describe the facility itself.

The wing spillage facility in figure 2-1 is powered by the low pressure fan discharge air produced by a TF33 engine. This unvitiated air is ducted into the throat of a 20-foot by 20-foot bellmouth, thus inducing ambient air to flow into the bellmouth. The two airstreams, the fan air at 500 knots and the induced ambient air, at low velocity, mix in a 50-foot long square augmentor duct (69 by 69 inches). At the exit of the square duct the primary and induced flow mix is fairly uniform and the velocity profile is almost flat. This stream exhausts from the augmentor duct and flows over a simulated wing section located 16 feet downstream at the projected horizontal centerline of the augmentor. In the leading edge of this wing section projects a 12-inch pipe on which a variety of discharge orifices can be mounted. During a test, the fuel is forced through the leading edge orifice and released into the counterflowing airstream. Three feet below the horizontal centerline and 4 1/2 feet aft of the fuel release point, a large propane torch is mounted. This torch in still air produces a flame 5 feet long, 8 inches in diameter and burns at about 1100° F. The relative position of an engine installation (for fuel ingestion testing) and one of the aft propane torch locations are also shown in figure 2-1. It should be noted that usually only one of the ignition sources is used during any particular test, i.e., during engine ingestion tests only the engine is involved in the test; the aft propane torch and the underwing torch would not be operative. For reference purposes, the standard configuration is defined herein as that which uses the propane torch only in the underwing location. Using this apparatus, a variety of tests were conducted to determine some of the flammability characteristics of the antimisting fuel. The primary instrumentation in these studies was photographic and the intent was to quantify test results. The approach used was to measure a fireball as it developed by outlining each fireball silhouette at time increments of 1/20th of a second and measuring the area change as a function of time. Figure 2-2 is a typical series of fireball silhouettes developed from a high speed film of a test. In this particular test the fire developed at a relatively low rate. The area of each silhouette was measured and an equivalent area circle was then computed. The rate of change of radius of the equivalent circle was then used as one of the parameters to define the character of the fireball development. In this figure, there are 11 separate silhouettes which encompass a time period of 11/20ths of a second. Having established the procedure of measuring the fireball, a plot of fireball size versus time was used to establish yardsticks for what was considered a "pass" or "fail" test of the AMK.

For purposes of the tests reported herein a fireball growth rate of 10 feet per second or less was considered a pass and 20 feet per second and greater was considered a fail. Figure 2-3 is a plot of fireball radius growth versus time, for the silhouettes shown in the previous figure (figure 2-2). The relatively low growth rate, 5.2 indicates that this was a pass test for the fuel. Figure 2-4 is a

2-1

plot of a test which was run at an air-shearing relative velocity 10 knots higher than the previously described test and resulted in a fireball radius growth rate of 20.1 feet per second. This test was rated as a fail for the fuel. Having established the criteria to be used in evaluating the antimisting fuels flammability, the following series of tests were conducted.

There are 10 categories of tests tabulated in figure 2-5, encompassing a variety of parameters which were considered to be worthy of investigation. They ranged from jet A baseline tests to engine ingestion and relative air velocity deceleration tests. For purposes of this discussion, only the major categories of tests will be discussed in some detail. These included the parameters listed in the figure 2-6 tabulation.

The other categories covered in the tests had only minimal impact on the antimisting performance of the fuel. These other tests included the following: (1) various ignition sources such as rockets, a jet engine, and aft propane torches; (2) the effect of the orifice shape, roughness, or size was also tested; and (3) some preliminary investigations of the antimisting fuel performance during a simulated deceleration of the relative velocity.

All these parameters had only minor impact on the antimisting performance of the fuel. Details of these tests are covered in Report No. FAA CT-81-11.

1. The first of the major test categories was the jet A baseline tests. The jet A tests were conducted with the standard test configuration, i.e., an underwing propane torch as the ignition source. The results of two such tests are shown in figure 2-7. There were two separate spillage rates for the jet A, 20 and 60 gallons per second (gps). They resulted in almost explosive fireballs which had growth rates of 48 and 80 feet per second, respectively. This level of growth was more than twice as high as that which would be considered a fail with the antimisting fuel. It should also be noted that the fire propagated forward to the most forward point in the fuel stream against an airstream relative velocity as high as 130 knots. Figures 2-8 and 2-9 show the contrast between jet A test and a "marginal" (11-19 feet per second test with AMK).

2. The second set of tests of significance dealt with air shearing relative velocity as the variable. These tests were conducted in the standard test configuration using 0.3 percent antimisting fuel at fuel temperatures of 80° F + 3° F. The results of these tests are shown in figure 2-10 which indicate that the fuel was in the pass region up to 125 knots and in the fail region at 135 knots and above.

3. The next category of tests explored the impact of fuel temperature on the flammability characteristics of the antimisting fuel. The standard test configuration was employed and the results of these tests are shown in figure 2-11. It is apparent that a definite change occurs as a result of fuel temperature. Fuel at 47° F was in the pass region at relative velocities as high as 133 knots and when the fuel temperature was raised to 110° F, the pass region relative velocity was lowered to 116 knots. It is significant to note that the 110° F fuel temperature is above the minimum specification limit for jet A flash point.

4. The fourth major category of tests dealt with additive concentration. These tests were conducted using the standard test configuration, fuel temperature of 80°

F + 3° F a 20-gallon per second spillage rate, and a range of additives concentrations from 0.2 to 0.4 percent. Figure 2-12 displays the results of these tests. FM-9 at 0.2 percent concentration was in the pass region at relative velocities up to 99 knots relative air-shearing velocity and 0.4 percent FM-9 was in the pass region at relative velocities as high as 174 knots. Additive concentration appeared to be the single most important factor affecting the antimisting performance of the fuel during the tests conducted with the wing spillage facility.

5. The fifth category to be discussed was the investigation of spillage rate effects. These tests were conducted using the standard test configuration fuel at temperatures of 80° F + 3° F and 0.3 percent additive concentration, air shearing relative velocities from 120 to 150 knots, and spillage ranging from 20 to 60 gallons per second. The impact of spillage rate on the flammability of the fuel was considered to be one of the major points to be resolved by the spillage tests. The results of these tests are shown in figure 2-13. It is clear that over the spillage rate range shown (20 to 60 gallons per second), spillage rate did not appear to have a major effect on the antimisting performance of the fuel. The 20 gallon per second pass level was 125 knots and 60 gallons per second had a pass level at 130 knots. However, this minor shift might not actually exist if the ignition source for the 60 gallons per second spill had been located further back from the release point where the fuel/air mix would have been more representative of the ratio of the mix for the 20 gallons per second spill rate.

In summary, the results of the tests indicate that the most significant factor affecting the flammability characteristics of undegraded FM-9 are: (1) additive concentration, (2) air-shearing velocity, and (3) fuel temperature.
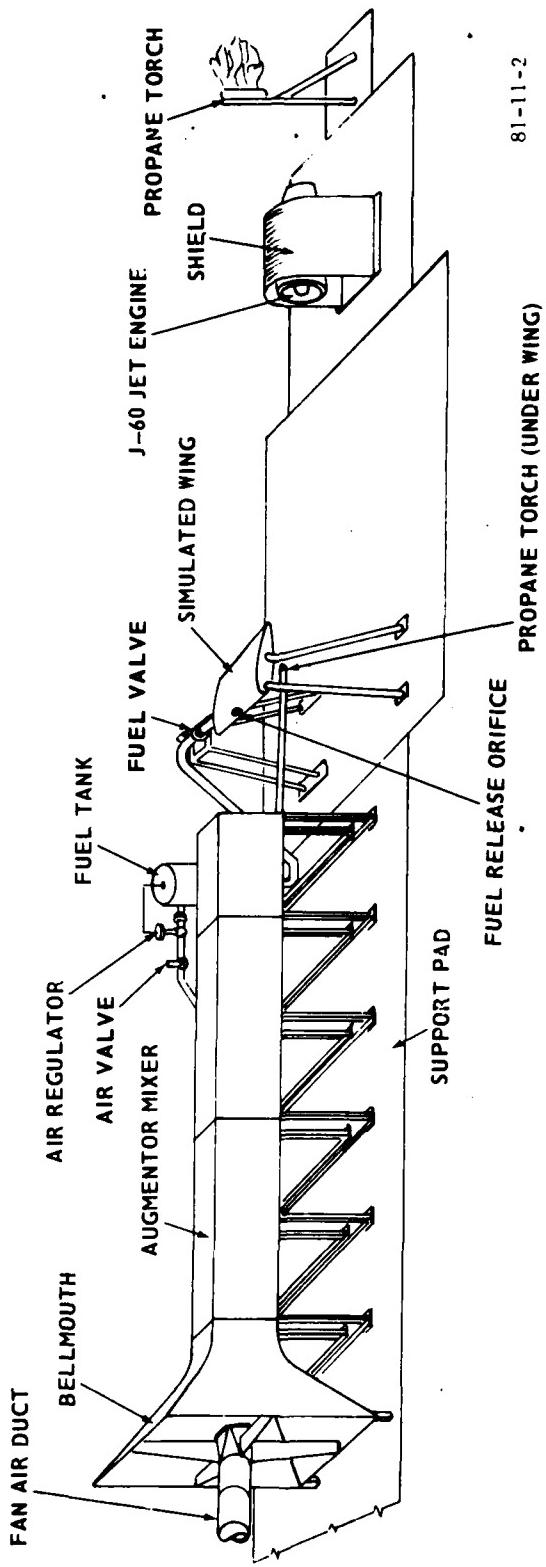
FIGURE 2-1. WING SPILLAGE TEST FACILITY

81-11-2

2-4
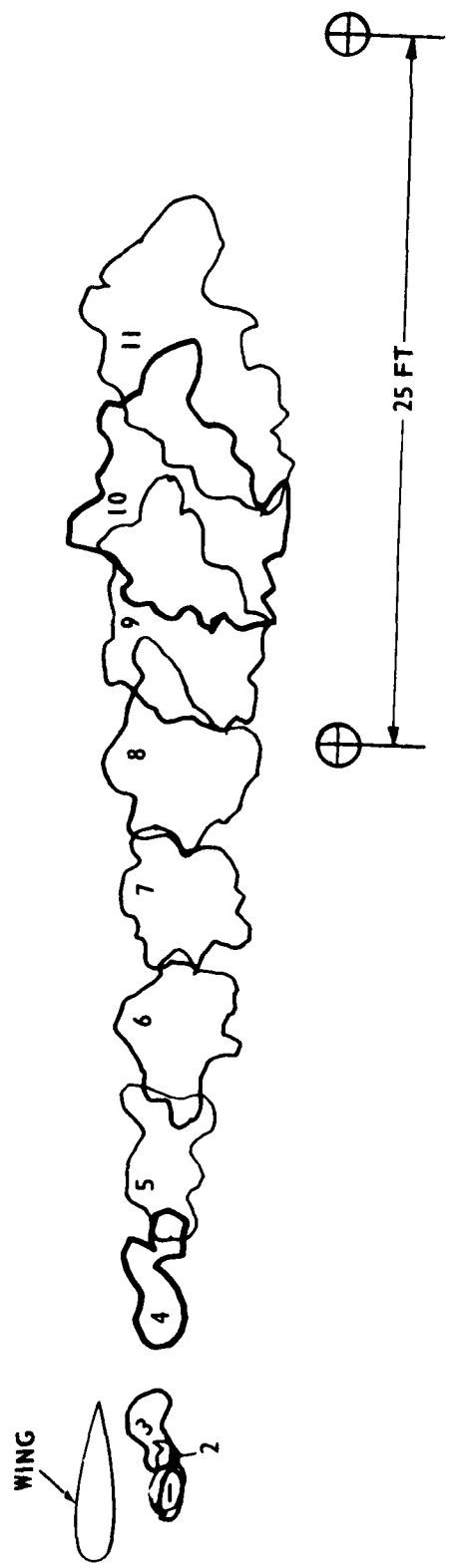
FIGURE 2-2. FIREBALL SILHOUETTES OF TEST NO. 64

2-5

TEST #64
FUEL TEMP: 48° F
AIR SPEED: 130 KNOTS
FM-9 CONC: 0.3%
SPILLAGE RATE: 20 GPS
IGNITION: I CONT. PROPANE
TORCH UNDERWING

SLOPE 5.18 F/S

EFFECTIVE FIREBALL RADIUS (FEET)

TIME (SECONDS)

81-11-16
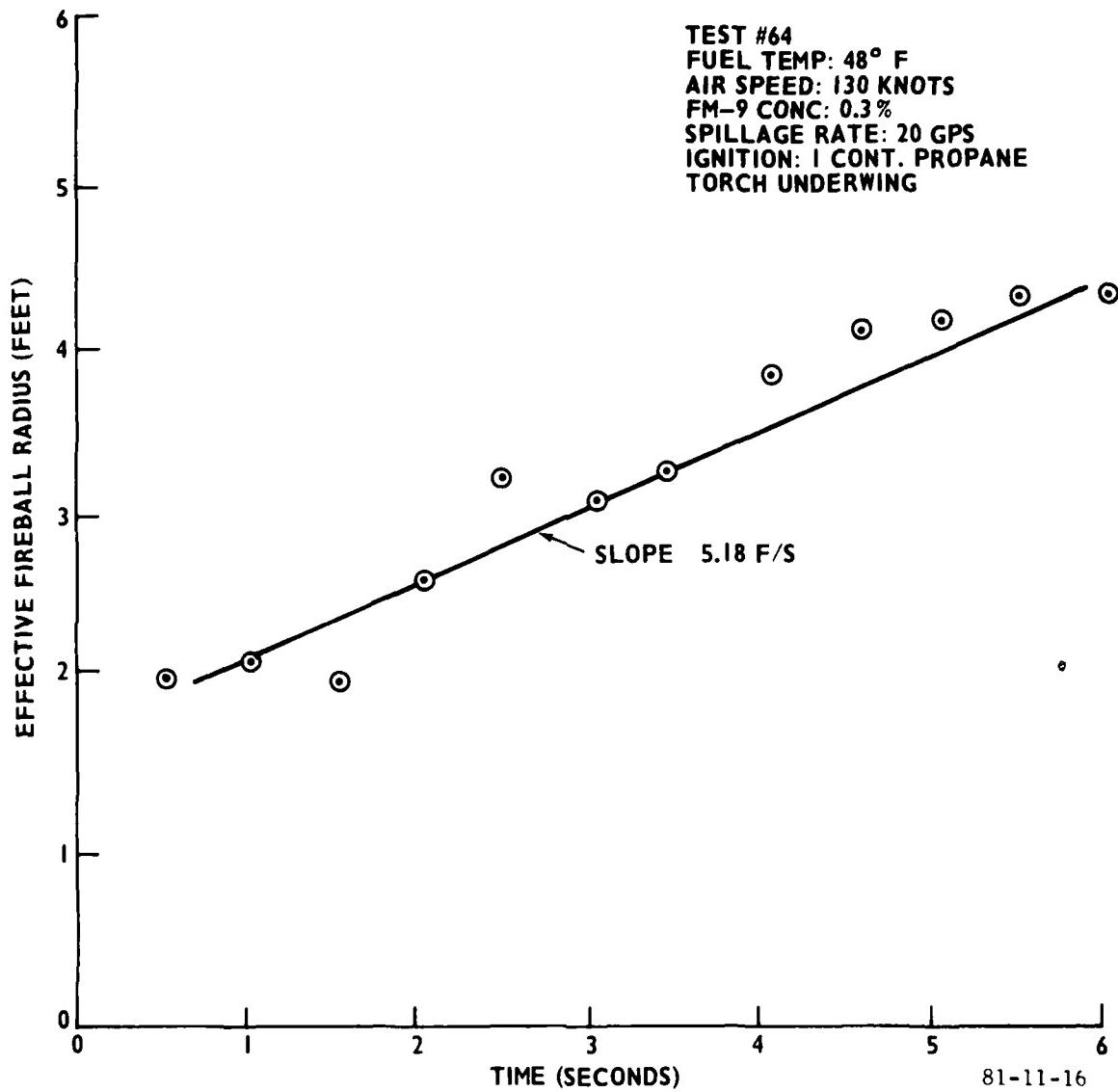
FIGURE 2-3. EFFECTIVE FIREBALL RADIUS VS. TIME (NO. 64)

2-6
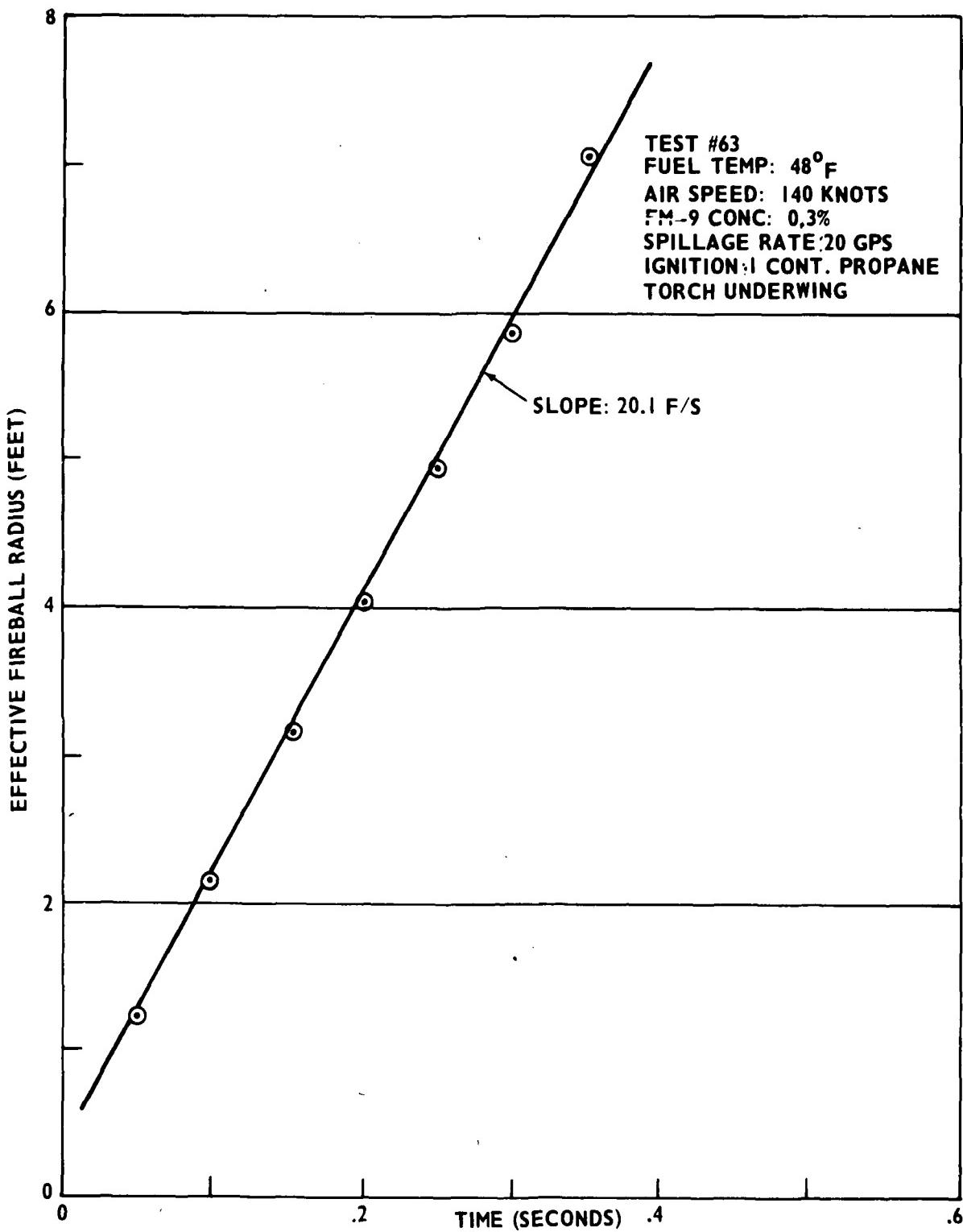
FIGURE 2-4. EFFECTIVE FIREBALL RADIUS VS. TIME (NO. 63)

1. JET A BASELINE TESTS

2. AIR SHEARING VELOCITY EFFECTS ON AMK

3. SPILLAGE RATES

4. FUEL TEMPERATURE EFFECTS ON AMK

5. FUEL CONCENTRATION EFFECTS ON AMK

6. ROCKET IGNITION TESTS

7. SPILLAGE HEIGHT ABOVE GROUND

8. ORIFICE CONFIGURATION EFFECTS ON AMK

9. ENGINE INGESTION TESTS

10. DECELERATION TESTS

FIGURE 2-5.   TESTING CATEGORIES

1. JET A BASELINE TESTS

2. VELOCITY EFFECTS

3. FUEL TEMPERATURE EFFECTS

4. FUEL CONCENTRATION EFFECTS

5. SPILLAGE RATE EFFECTS

FIGURE 2-6.   MAJOR TEST CATEGORIES
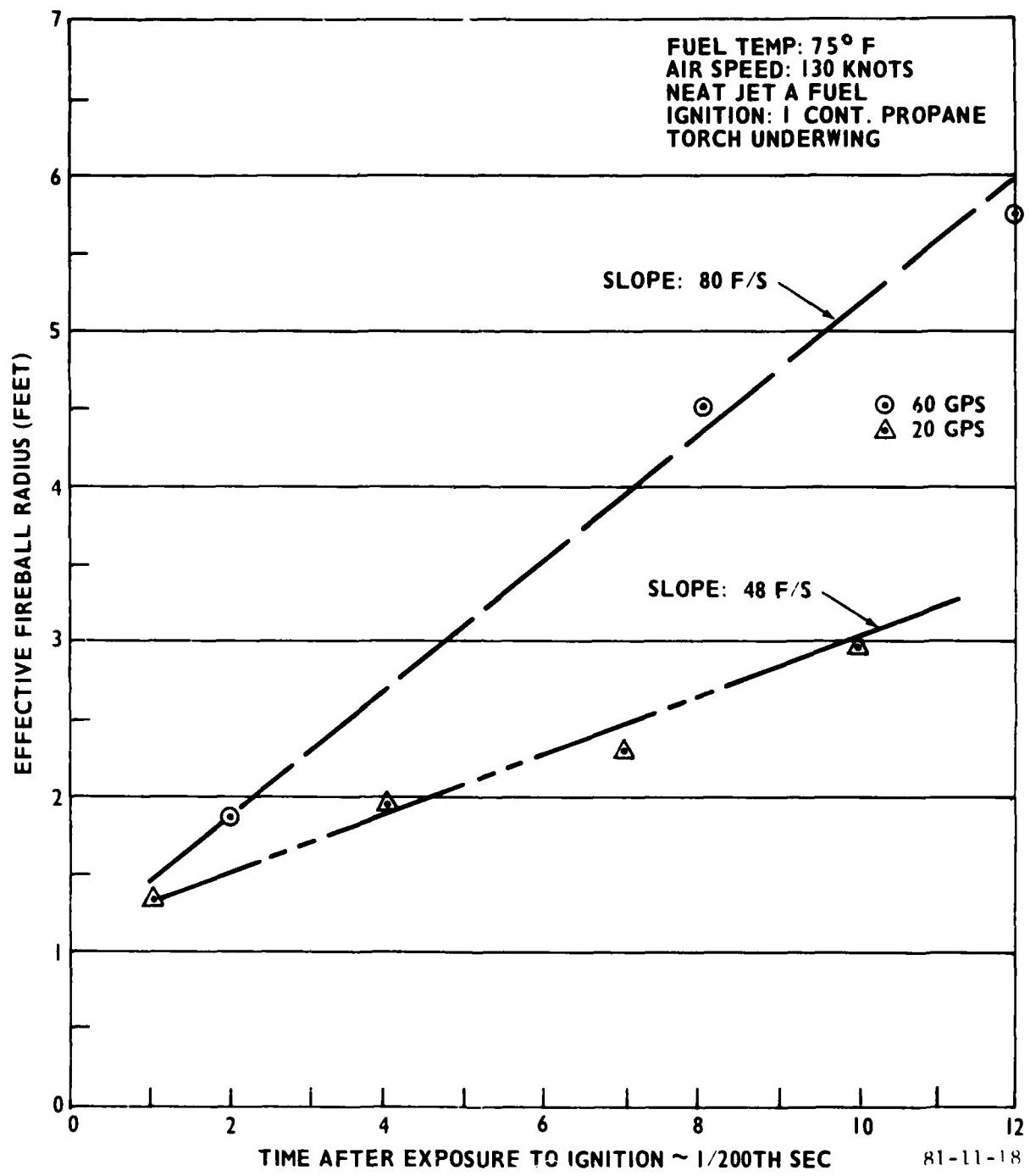
FIGURE 2-7.   JET A BASELINE TEST RESULTS

2-9

FIGURE 2-8. JET A, WING SPILLAGE TEST

80-3921

FIGURE 2-9. MARGINAL AMK, WING SPILLAGE TEST
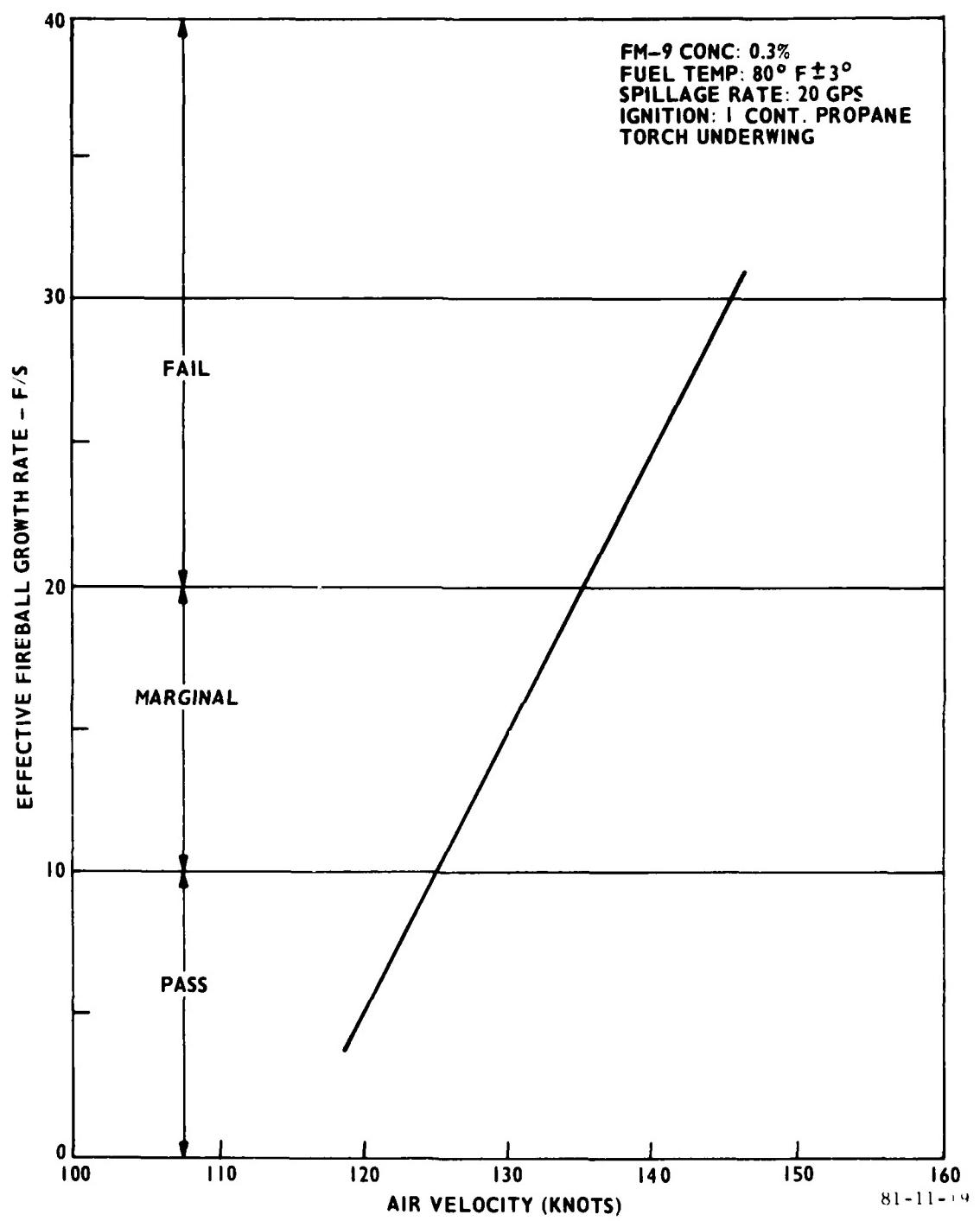
FIGURE 2-10. GROUP 2 RESULTS (VELOCITY)
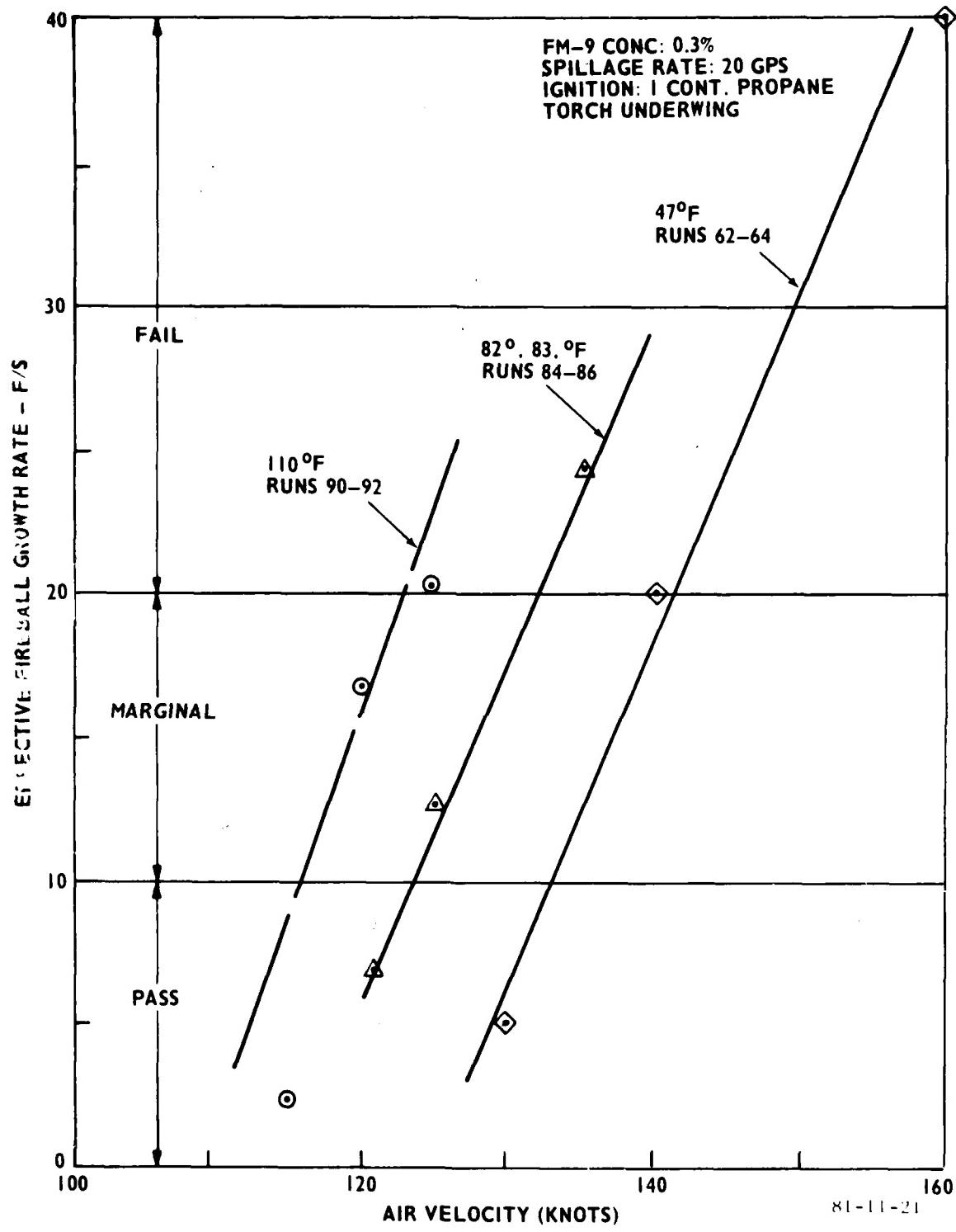
FIGURE 2-11.   GROUP 4 RESULTS (FUEL TEMPERATURE)
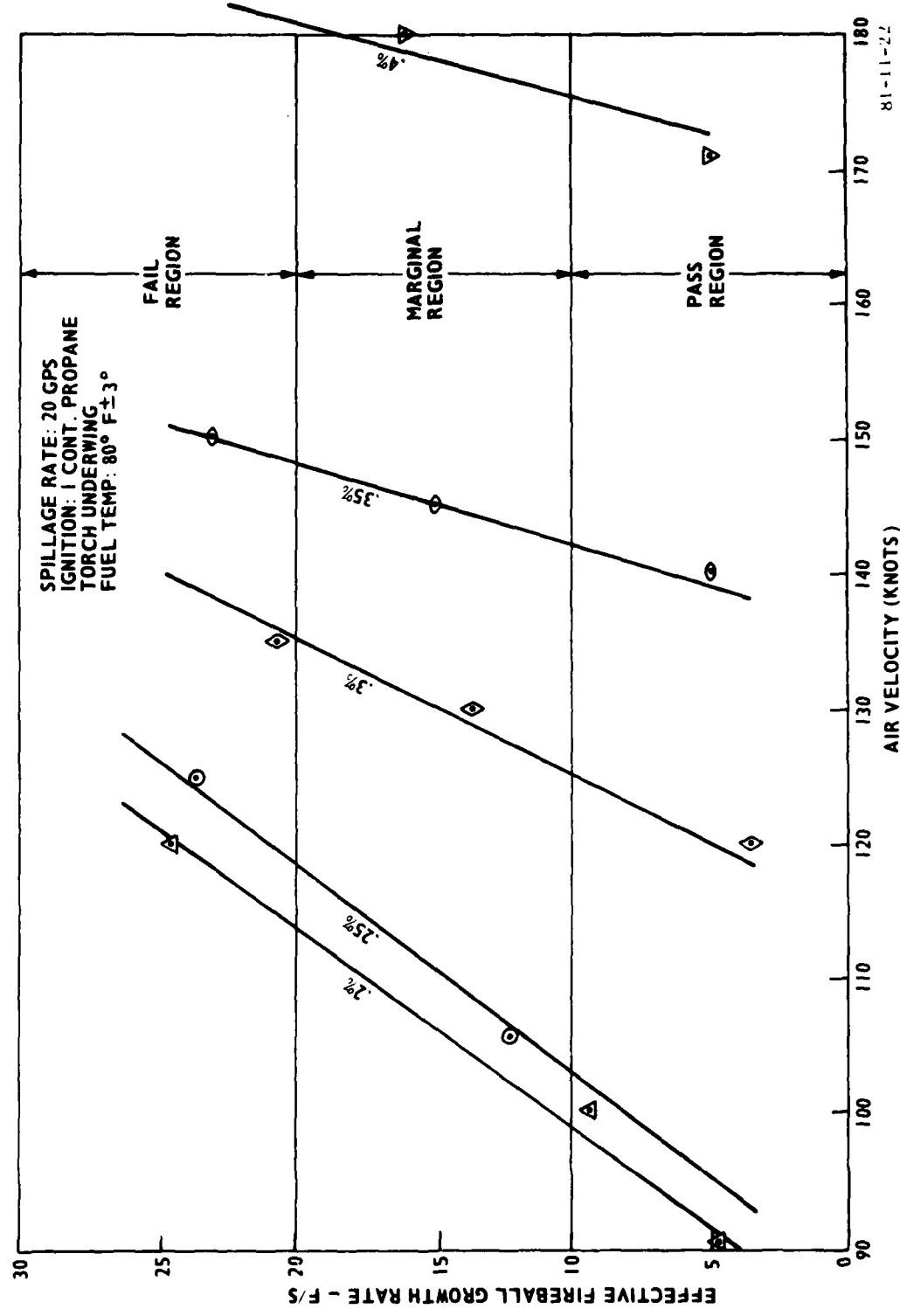
FIGURE 2-12. GROUP 5 RESULTS (FUEL ADDITIVE CONCENTRATION)

2-14
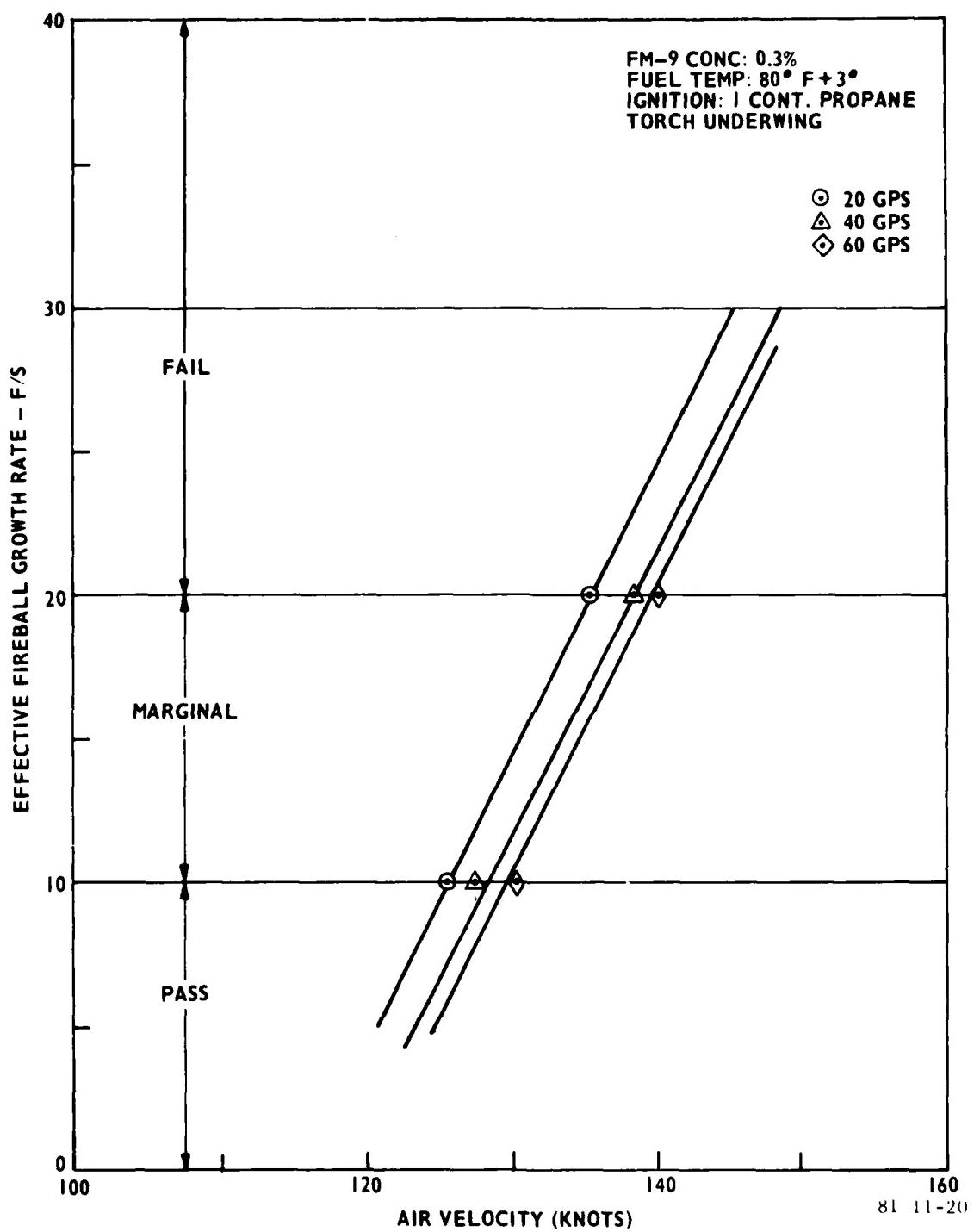
FIGURE 2-13. GROUP 3 RESULTS (SPILLAGE)

2-15

FLAMMABILITY COMPARISON TEST APPARATUS

By

E.P. KLUEG

FAA TECHNICAL CENTER

The Flammability Comparison Test Apparatus (figure 2-14) was developed by the FAA so that each organization involved in antimisting fuel research efforts would have comparable equipment for studying the flammabilty of antimisting fuels. The primary design criteria for this equipment was: probability, repeatability, minimal fuel consumption, and variable air and fuel flow rates. Units were built for:

Jet Propulsion Lab
Southwest Research Institute
NASA Ames
NASA Lewis
Royal Aircraft Establishment
FAA Technical Center

The apparatus consists of three subsystems (figure 2-15) controlled by a timer. The first system is a propane torch which serves as an ignition source for the fuel. The second subsystem provides air through a sonic orifice into a mixing tube and nozzle. Fuel is supplied by a piston pump into the mixing tube and is sheared by the high velocity air. The fuel/air mixture is then exposed to the propane ignition source (figure 2-16). A test consists of a number of 10-second runs with varying air and fuel flow rates. A radiometer is used to determine the heat flux prior to flame propagation, the rate of change of heat as the flame propagates, and the maximum heat output. Figure 2-17 shows a test utilizing neat jet a fuel. A typical trace for jet A fuel is shown in figure 2-18. The significant measurements are the maximum heat rate: (a) the threshold heat, (b) the rate of change of heat, and (c) the initial jet A vapor heat release.

In comparison, an antimisting fuel trace with good fire resistance characteristics is shown in figure 2-19. If the air and fuel flows are increased until the antimisting fuel fails, the resulting trace would be similar to that shown for jet A in figure 2-17.

Tests with FM-9 and jet A indicate the flammability comparison test apparatus provides useful information for screening antimisting fuels. As presented in the paper by Levelle Mahood and Robert Talley of Falcon Research and Development, work is continuing on correlating results obtained from this experiment with other laboratory and large-scale tests.

FIGURE 2-14. FLAMMABILITY COMPARISON TEST APPARATUS (FCTA)

2-17
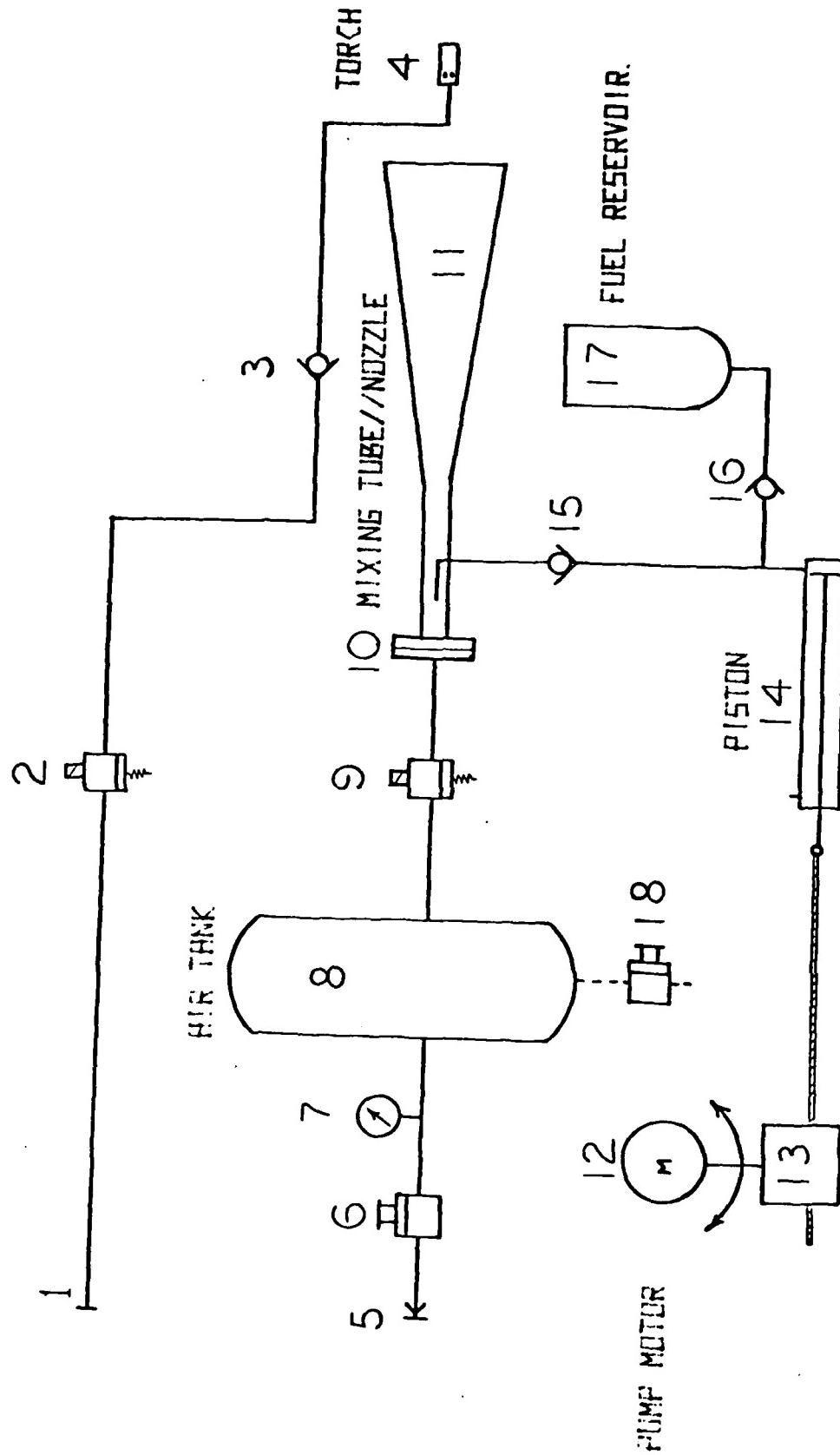
FIGURE 2-15.   SCHEMATIC OF FLAMMABILITY COMPARISON TEST APPARATUS

2-18
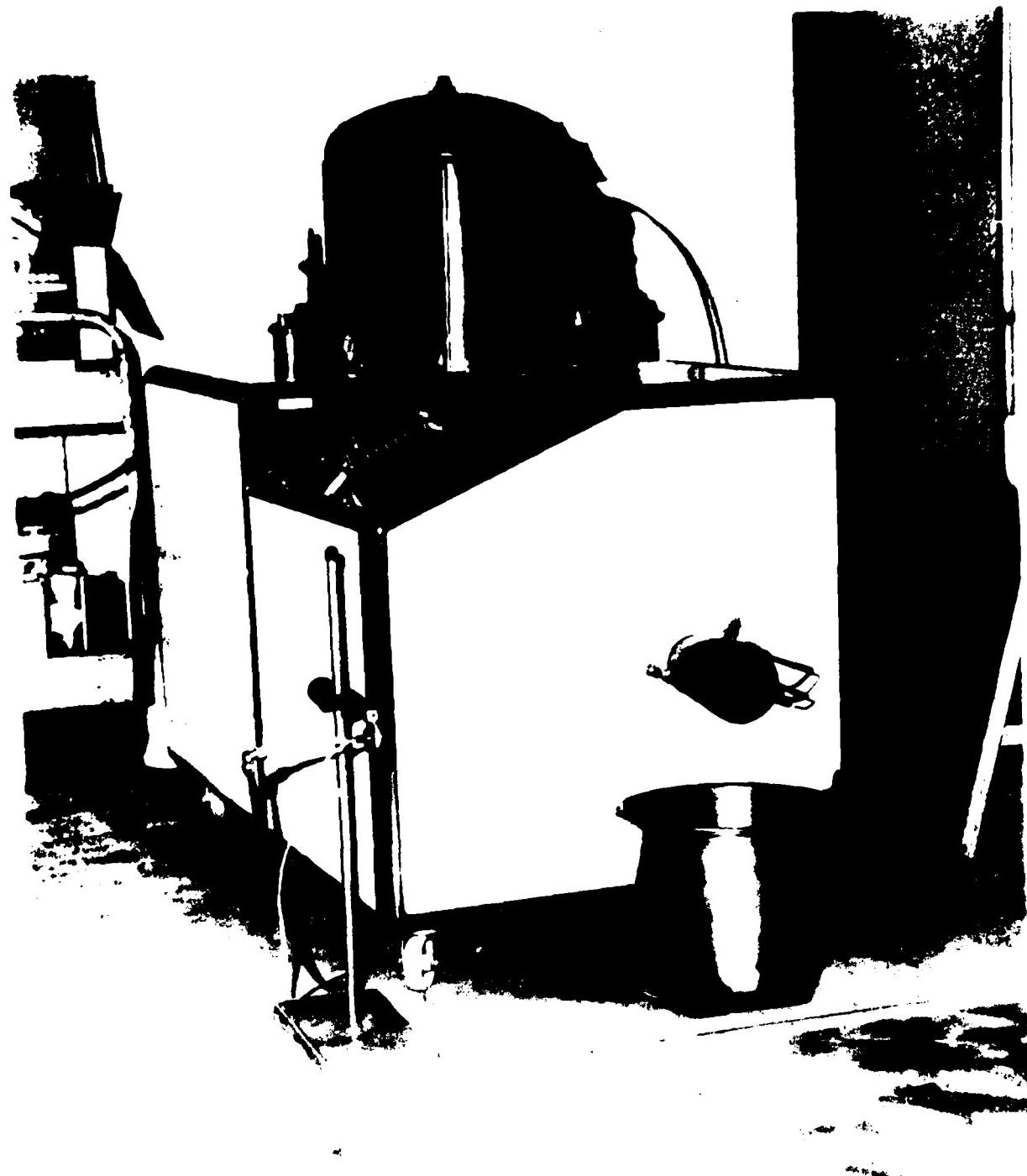
FIGURE 2-16.   FLAMMABILITY COMPARISON TEST APPARATUS (FCTA) - SIDE VIEW

2-19

FIGURE 2-17. FLAMMABILITY COMPARISON TEST APPARATUS (FCTA) TEST WITH JET A FUEL
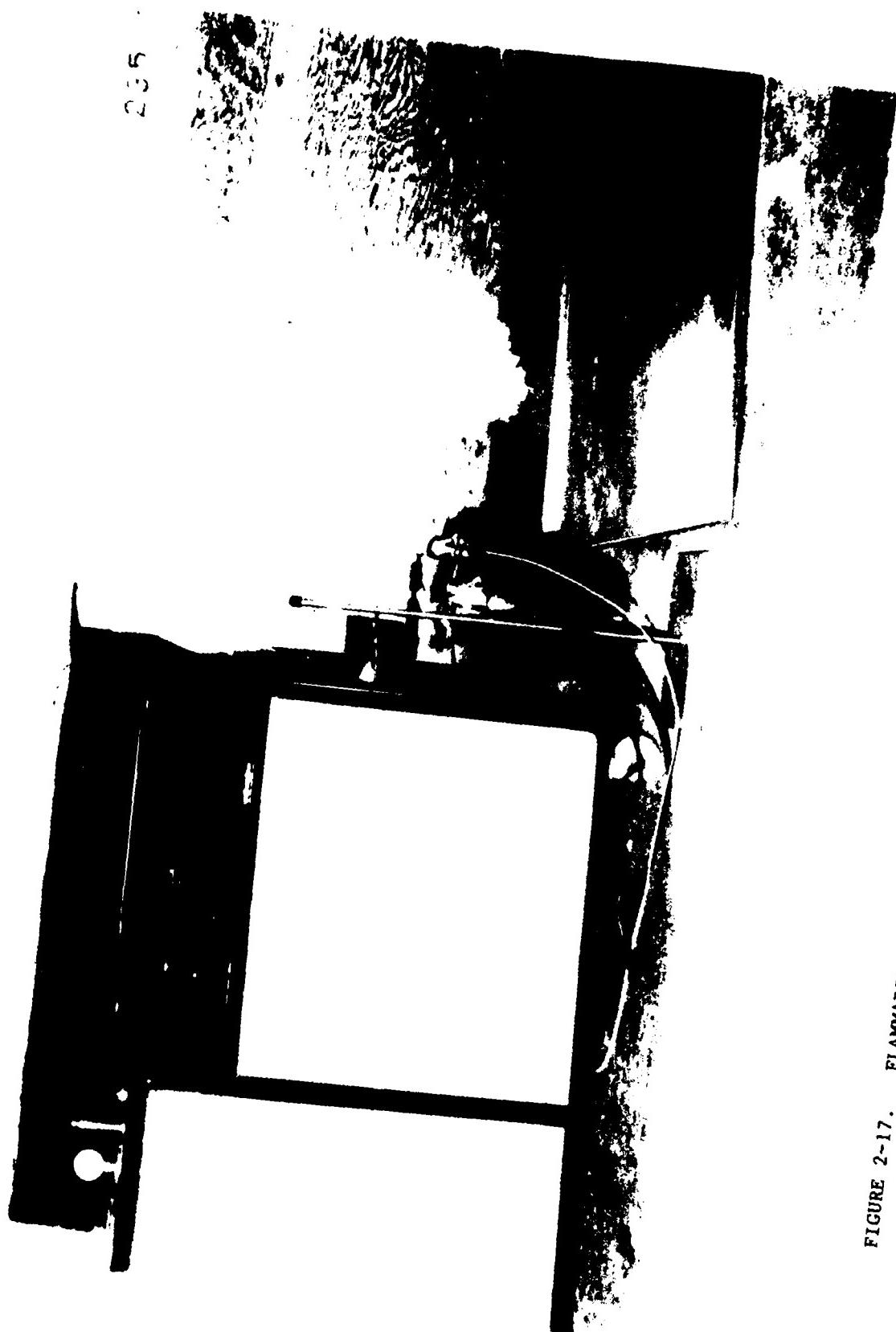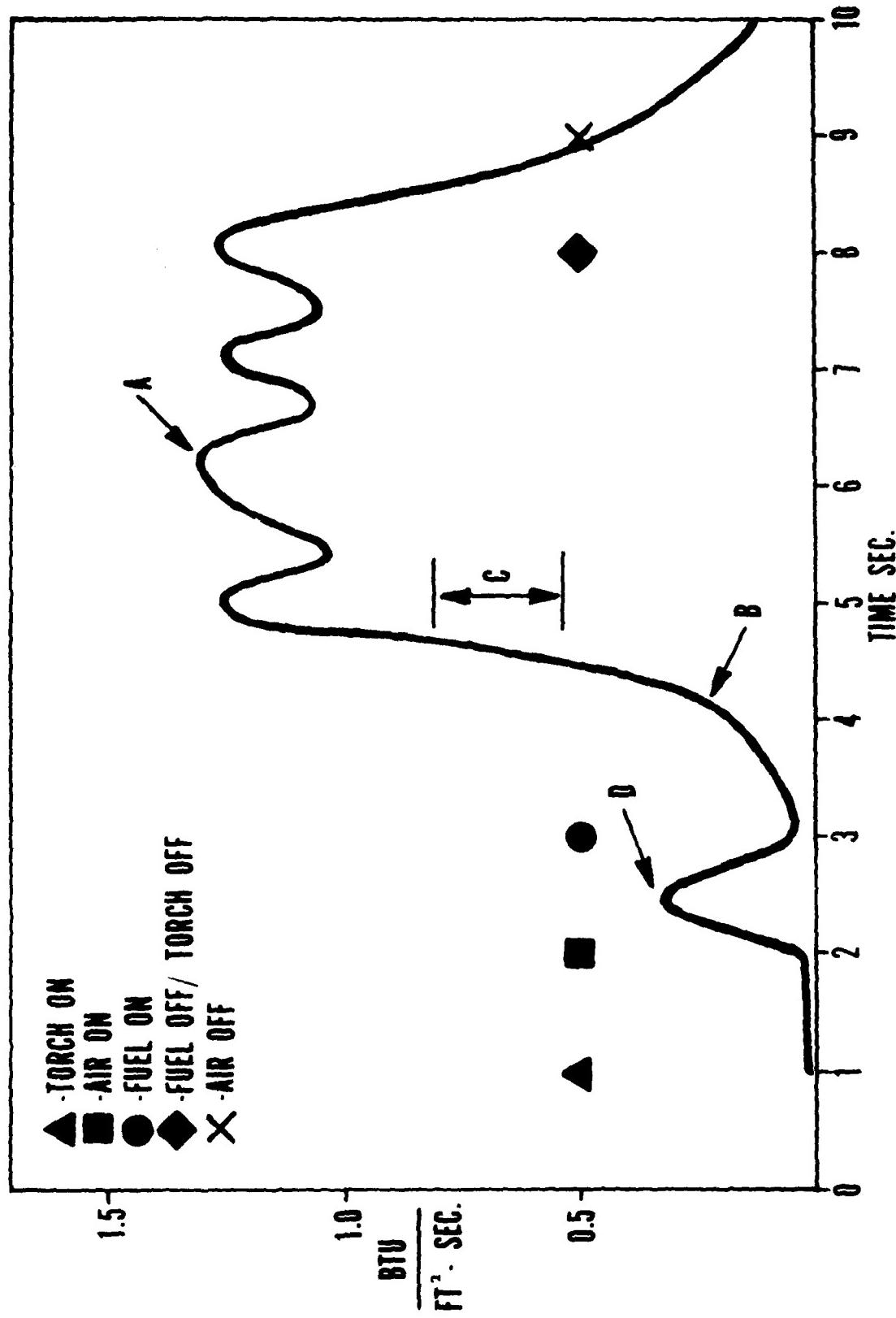
FIGURE 2-18. TYPICAL OSCILLOGRAPH TRACE FOR A JET-A FAIL, HEAT OUTPUT VERSUS TIME

Legend:
▲ -TORCH ON
■ -AIR ON
● -FUEL ON
◆ -FUEL OFF / TORCH OFF
✕ -AIR OFF

Y-axis: $\frac{BTU}{FT^2 \cdot SEC.}$

X-axis: TIME SEC.
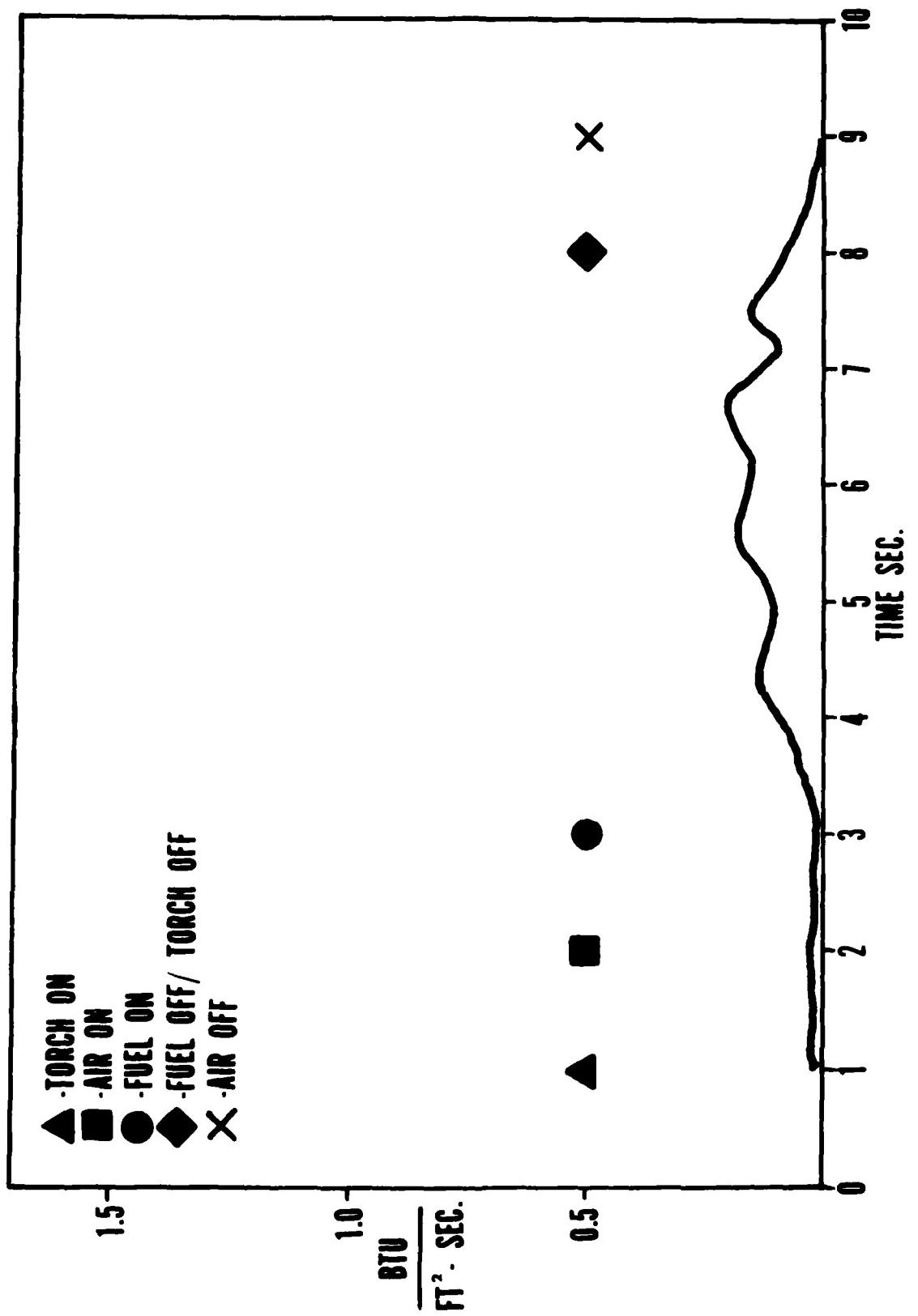
FIGURE 2-19. TYPICAL OSCILLOGRAPH TRACE FOR A PASS HEAT OUTPUT VERSUS TIME

LARGE-SCALE AIRCRAFT CRASH TEST OF ANTIMISTING FUEL

By

E.P. KLUEG

FAA TECHNICAL CENTER

The FAA entered into an agreement with the Naval Air Engineering Center at Lakehurst, N.J., in September 1978, to conduct large-scale tests to evaluate antimisting fuel. Five SP-2H aircraft would be propelled along a jet track, the wing tanks ruptured, and the aircraft crashed on a 3° dirt slope with open flame ignition sources. In order for the aircraft to be compatible with the track site, weight and size reductions to the aircraft were accomplished (figure 2-20). Further modifications were made to assure that the fuel tanks ruptured and the expelled fuel was exposed to open flames. Figure 2-20 shows the first crash vehicle positioned on a shuttle frame. Knife blades have been installed over the wing to puncture the fuel tanks inboard of the reciprocating engines. The wing leading edge has been removed and knife blades installed to puncture the six-fuel bladder in each wing, outboard of the reciprocating engines.

Figure 2-21 shows the leading edge knife blade mechanism for the port wing. In addition to the two reciprocating engines, the SP-2H aircraft have two jet engines which normally operate on 115/145 grade aviation gas (AVGAS).

A jet car, powered by four J-48 jet engines shown in figure 2-22 propel the shuttle frame to which the crash vehicle is secured. The inboard wing knife blade mechanism is also shown in this photo. Rocket motor canisters were installed on each slide of the aft fuselage, each containing seven 2.75 inch rocket motors.

Figure 2-23 shows the port canister and another view of the inboard wing knife blades. The cables which pull-out the interconnect hoses between the inboard fuel tank bladders are also shown below the wing. The bridle and holdback cables which secure the crash vehicles to the shuttle are shown.

The crash site is shown in figure 2-24. The track which is not shown, would be to the right. After the crash vehicle is accelerated along 6,190 feet of the track, the jet car separates from the aircraft and shuttle. Nine-hundred feet further down the track, the aircraft separates from the shuttle, the rocket motors are ignited, and the inboard fuel tanks are ruptured. The crash vehicle continues for another 180 feet before the outboard fuel tanks are ruptured and another 20 feet before the main gear are sheared and the inboard fuel tank interconnects are pulled (at station 0). At station 91, the nose gear is sheared and aircraft starts to impact a 3° earth slope. The first line of smudge pots are at station 144. The remaining 44 to 49 smudge pots are positioned on the 70- by 800-foot earth pillow between stations 164 and 844.

Four tests have been conducted during the last 1 1/2 years (figure 2-25). The first was a jet A baseline test with a 117 knot impact ground speed (120-knot relative airspeed). The maximum longitudinal acceleration was 5.5 G's, 0.6 second after shearing the main gear. The crash vehicle came to rest at station 610.

2-23

The second test was conducted with less than 0.3 percent FM-9 antimisting fuel and an impact ground speed of 94 knots (103-knot relative airspeed). The maximum G loading was 5.0 at 0.7 seconds. The crash vehicle came to rest 380 feet into the crash site.

The third test, also conducted with FM-9 antimisting fuel, was aborted during the initial launch phase and aircraft destroyed before reaching the crash site.

The fourth test was conducted with 0.27 and 0.30 percent FM-9 antimisting fuel and an impact ground speed of 118 knots (117-knot relative airspeed). The acceleration was 6.0 G's at 0.5 seconds. The crash vehicle came to rest at station 750.

The analysis of the high speed film of test number 1, summarized in figure 2-26 indicated that the port side inboard fuel was ignited by the rocket motors. Fuel spewing from the port wing was ignited by the first line of smudge pots and the fire propagated quickly to engulf the entire wing. On the starboard side, fuel spewing from the wing was ignited by the second line of smudge pots and again the fire propagated quickly to engulf the wing (figure 2-27). The wings and fuselage were substantially damaged by fire.

The analysis of the high speed film of test number 2, summarized in figures 2-28 and 2-29, indicated the inboard port side with 0.28 percent FM-9 fuel was ignited by the rocket motors. When the turbine engine separated from the wing, localized fire remained with the engine. The 0.26 percent FM-9 fuel on the starboard side was also ignited by the rocket motors. A fire also occurred in the vicinity of the turbine engine tail pipe. The results of this test showed that all the fire separated from the aircraft remained behind the aircraft and self-extinguished without forward propagation. Fires in the vicinity of the jet engines (figure 2-30) were due to the neat jet A fuel being used to operate these engines. The aircraft sustained no significant fire damage to the wings and fuselage.

Test number 4 was designed for a 125-knot impact speed with 0.27 and 0.30 percent FM-9 high specification fuel (figure 2-31). Based on FAA wing spillage tests, this would produce a clear pass for the 0.30 percent fuel and a marginal condition for the 0.27 percent fuel. Due to handling of the fuel, the fuel delivered to the aircraft was low-spec fuel (figure 2-32), based on quality control measurements. Since the aircraft impact speed was 8 knots low, this should have off-set the lower quality fuel. However, post-test analysis of a sample of the 0.27 percent fuel taken from the port wing indicated that the 0.27 percent fuel was contaminated with AVGAS. This moved the pass/marginal boundary for the contaminated fuel into the shaded area shown in figure 2-33 and the fuel into the fail area.

The analysis of the high speed film of test number 4, summarized in figures 2-34 and 2-35, indicates that the port side inboard fuel was ignited by the rocket motors. The fuel spewing from the outer port wing was ignited by the second line of smudge pots. The fire spread to the propane torch and attached to the outer section of the wing. The inboard fuel on the starboard side was also ignited by the rocket motors. Small fireballs developed as the wing impacted the smudge pots. Fires in the vicinity of the rocket motors, separated from the crash vehicle, remained behind and self-extinguished without forward propagation. The fire development and attachment to the port wing was due to the AVGAS contamination, the propane torch installation acting as secondary ignition source and flame holder, and the non-aerodynamic configuration of the outer wing. The small fire balls resulted from the liquid JP-5 fuel being expelled from the smudge pots when

2-24

aircraft. Although the 0.27 percent fuel produced more fire than expected, due to AVGAS contamination, the fuselage, starboard wing, and inboard port wing were not significantly damaged by fire.

Ongoing analysis of crash test number 4 and of test track capabilities are expected to establish whether any future large-scale crash tests are required prior to the full-scale B-720 crash test in 1984.

One of the primary purposes of the large-sclae crash tests is to substantiate that the results of the FAA wing-spillage tests are realistic and representative of an actual crash environment. The results to date indicate that this is the case.

FIGURE 2-20. MODIFIED SP-2H AIRCRAFT - FORWARD INBOARD PORT SIDE

FIGURE 2-21. MODIFIED SP-2H AIRCRAFT - OUTBOARD PORT SIDE

FIGURE 2-22. MODIFIED SP-2H AIRCRAFT - STARBOARD PORT SIDE

FIGURE 2-23. MODIFIED SP-2H AIRCRAFT - AFT INBOARD PORT SIDE
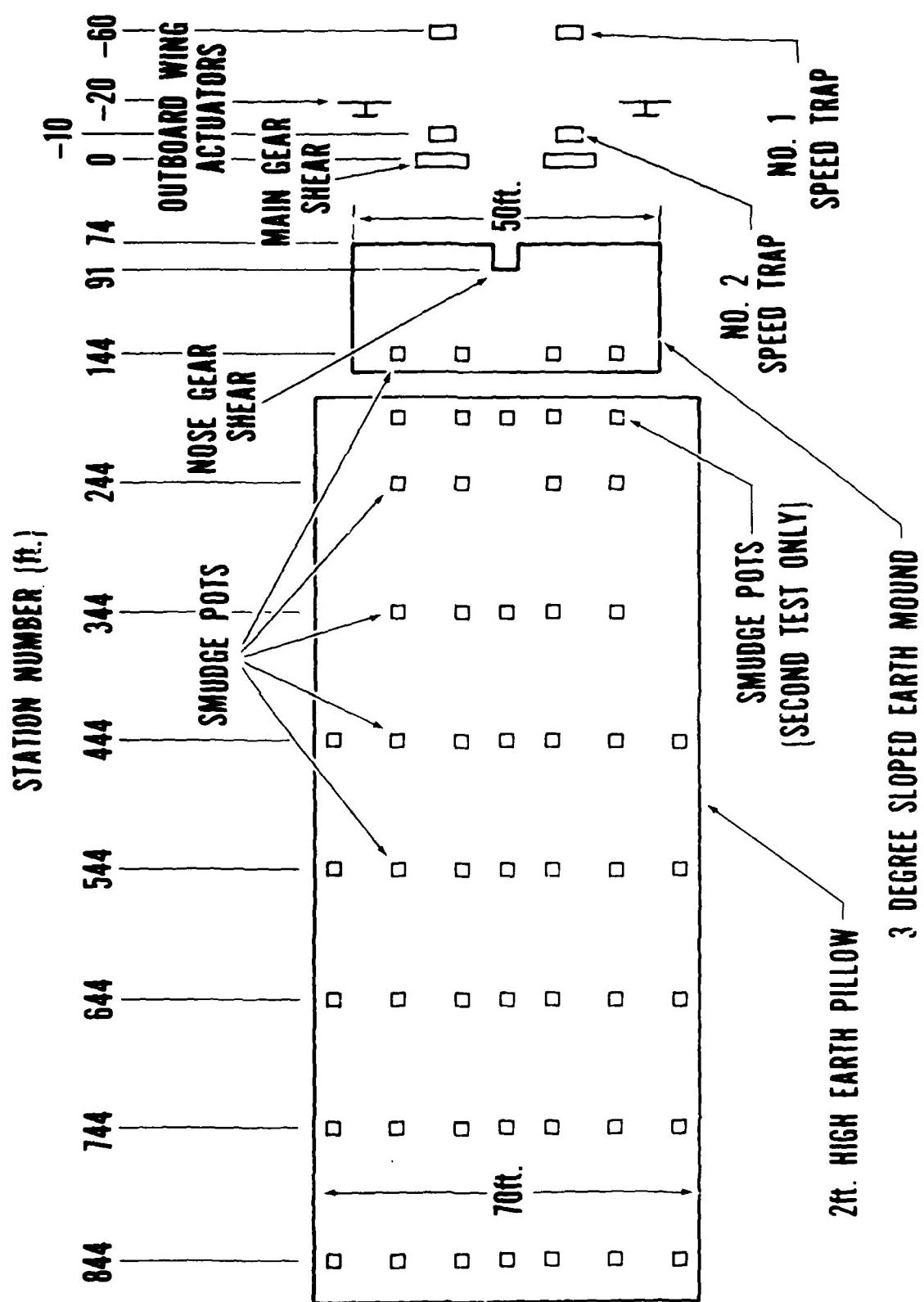
FIGURE 2-24. AIRCRAFT CRASH SITE

	TEST NO. 1	TEST NO. 2	TEST NO. 4
DATE	6/14/79	11/16/79	1/21/81
FUEL TYPE			
PORT WING	JET A	0.28% FM-9	0.27% FM-9
STARBOARD WING	JET A	0.26% FM-9	0.30% FM-9
FUEL TEMPERATURE (°F)	68	70	75
CUT-OFF SPEED (KNOTS)	130	115	128
SEPERATION SPEED (KNOTS)	119	99	–
IMPACT SPEED (KNOTS)	117	94	118
MAXIMUM G's	5.5 @0.6 SEC	5.0 @0.7 SEC	6.0 @ 0.5 SEC
AIRCRAFT POSITION (FEET)	610	380	750

FIGURE 2-25.   SP-2H AIRCRAFT CRASH TESTS DATA

PORT SIDE (NEAT JET A FUEL)

- INBOARD FUEL IGNITED BY ROCKET MOTORS

- FUEL SPEWING FROM WING IGNITED BY FIRST LINE OF SMUDGE POTS

- FIRE PROPAGATED QUICKLY TO ENGULF ENTIRE WING

STARBOARD SIDE (NEAT JET A FUEL)

- FUEL SPEWING FROM WING IGNITED BY SECOND LINE OF SMUDGE POTS
- FIRE PROPAGATED QUICKLY TO ENGULF WING

RESULTS

- WINGS AND FUSELAGE SUBSTANTIALLY DAMAGED BY FIRE

FIGURE 2-26.   SP-2H AIRCRAFT CRASH TEST NO. 1

FIGURE 2-27. CRASH TEST NO. 1 WITH JET A FUEL

PORT SIDE (0.28% FM-9 IN JET A FUEL)

- INBOARD FUEL IGNITED BY ROCKET MOTORS
- LOCALIZED FIRE AT TURBINE ENGINE

STARBOARD SIDE (0.26% FM-9 IN JET A FUEL)

- INBOARD FUEL IGNITED BY ROCKET MOTORS
- FIRE IN VICINITY OF TURBINE ENGINE TAIL PIPE

FIGURE 2-28. SP-2H AIRCRAFT CRASH TEST NO. 2

ROCKET MOTOR FIRES
- SEPARATED AND REMAINED BEHIND CRASH VEHICLE
- SELF-EXTINGUISHED WITHOUT FORWARD PROPAGATION

ENGINE FIRES
- DUE TO PRESENCE OF NEAT JET A FUEL

NO SIGNIFICANT FIRE DAMAGE TO WINGS AND FUSELAGE

FIGURE 2-29. SP-2 AIRCRAFT CRASH TEST NO. 2 RESULTS

FIGURE 2-30. CRASH TEST NO. 2 WITH ANTIMISTING FUEL

2-35
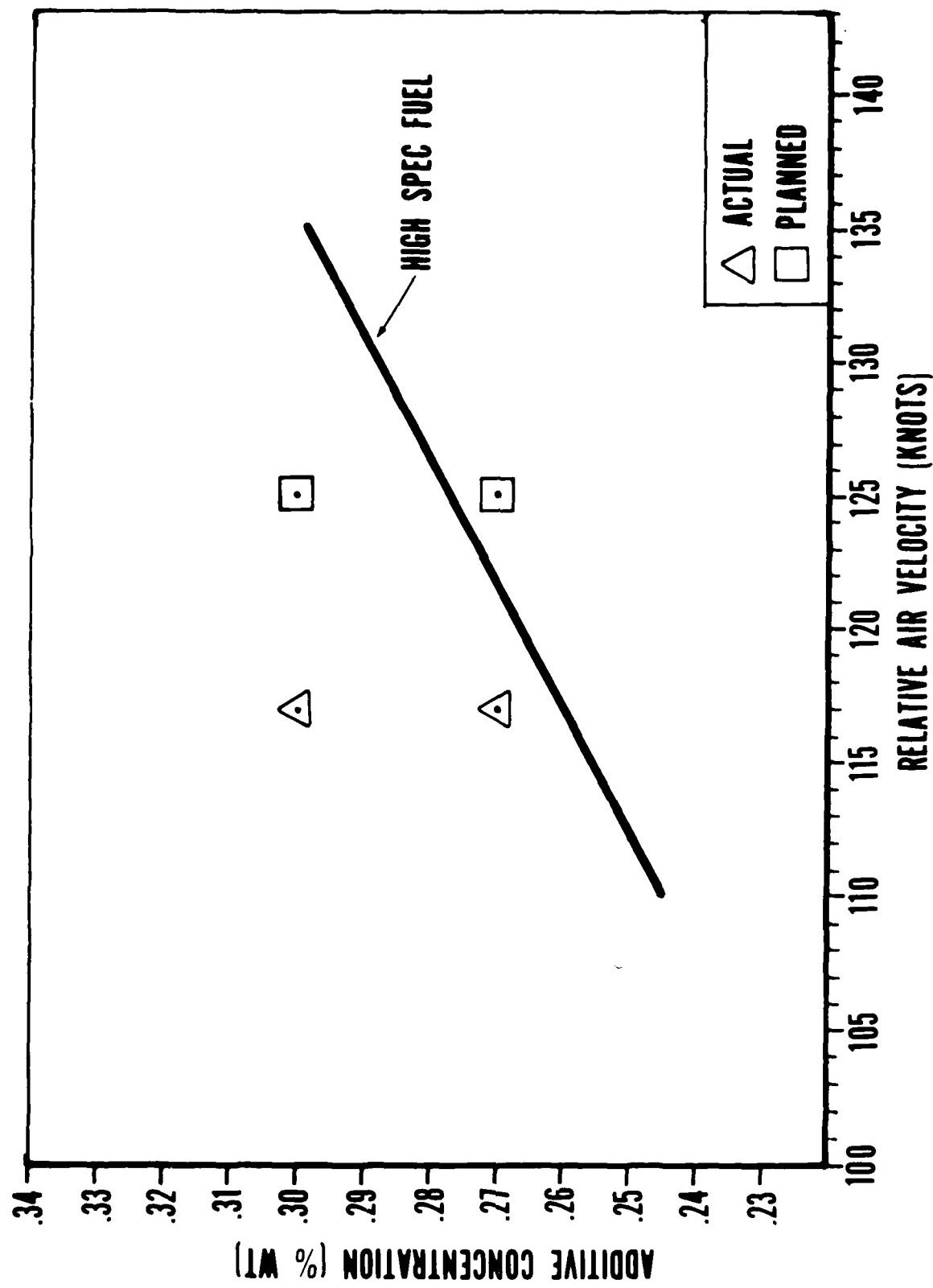
FIGURE 2-31.   CRASH TEST NO. 4 DESIGN - HIGH SPEC FUEL
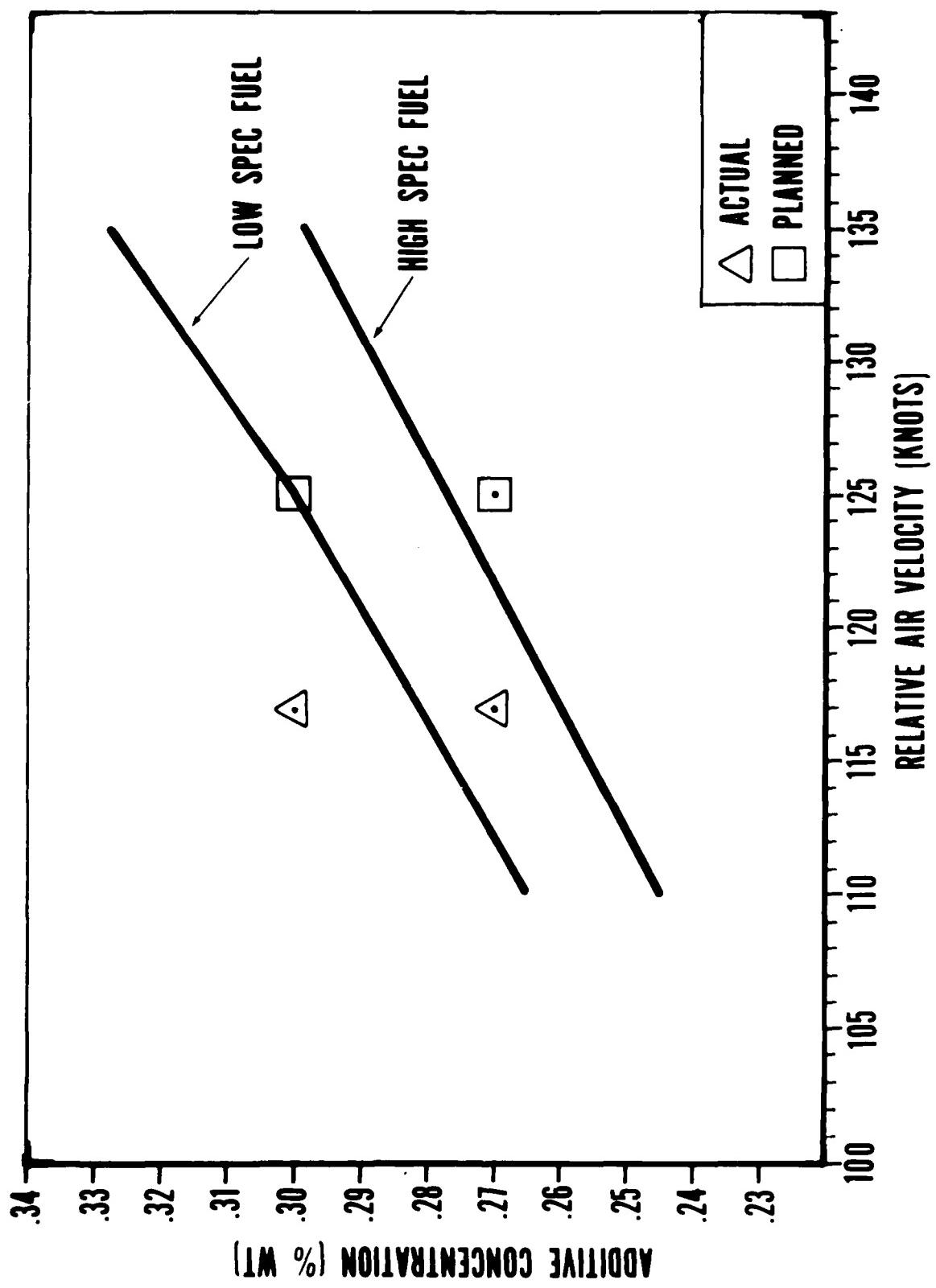
FIGURE 2-32. CRASH TEST NO. 4 DESIGN - HIGH AND LOW SPEC FUEL
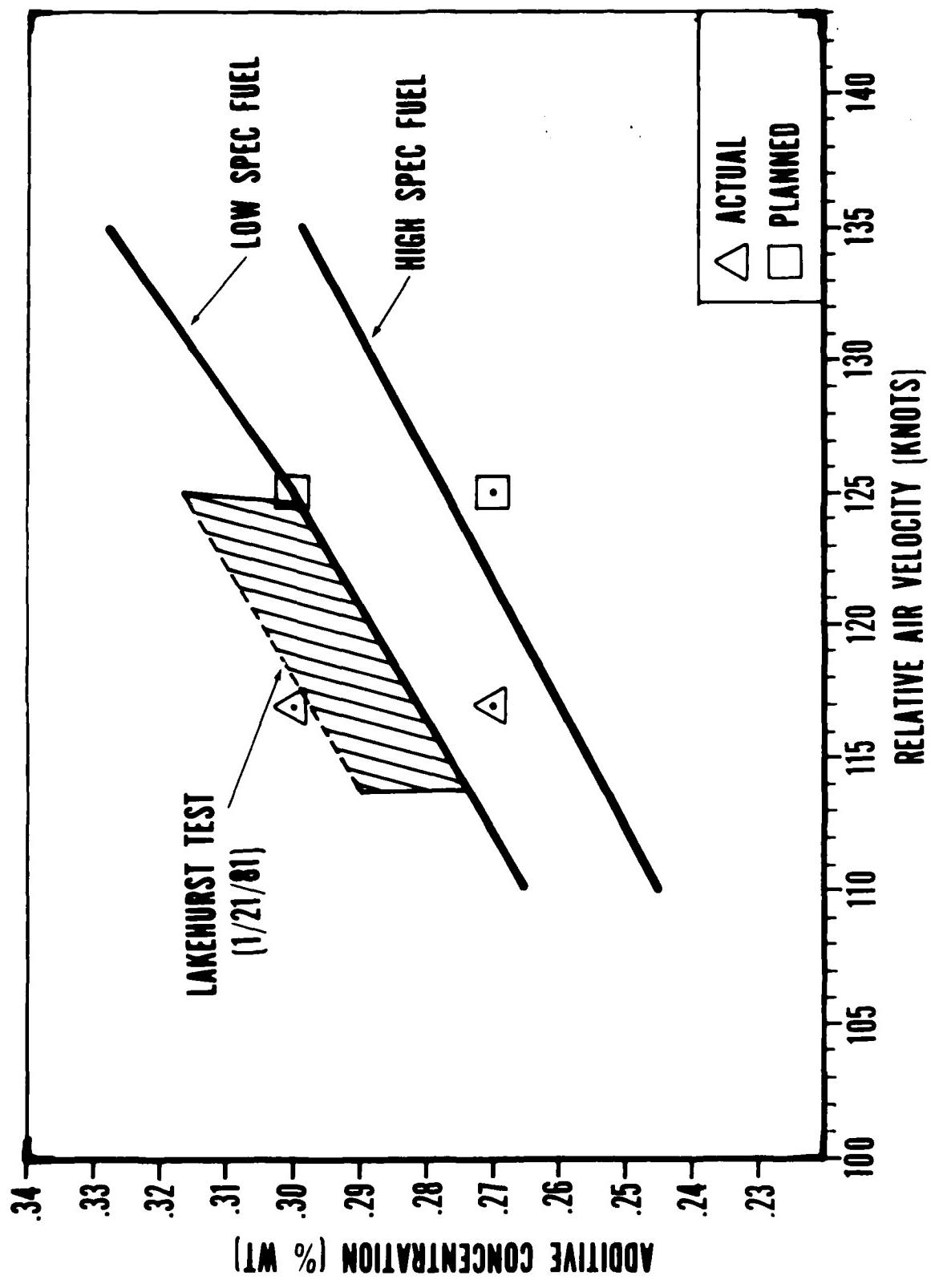
FIGURE 2-33. CRASH TEST NO. 4 DESIGN - SPEC AND CONTAMINATED FUEL

2-38

PORT SIDE (0.27% FM-9 IN JET A FUEL)

- INBOARD FUEL IGNITED BY ROCKET MOTORS
- OUTBOARD FUEL IGNITED BY SECOND LINE OF SMUDGE POTS AND
  FIRE SPREAD TO PROPANE TORCH AND ATTACHED TO WING

STARBOARD SIDE (0.20% FM-9 IN JET A FUEL)

- INBOARD FUEL IGNITED BY ROCKET MOTORS
- SMALL FIREBALLS DEVELOPED AS WING IMPACTED SMUDGE POTS.

FIGURE 2-34. SP-2H AIRCRAFT CRASH TEST NO. 4

ROCKET MOTOR FIRES
- SEPARATED AND REMAINED BEHIND CRASH VEHICLE
- SELF-EXTINGUISHED WITHOUT FORWARD PROPAGATION

PORT WING FIRE - DEVELOPMENT AND ATTACHMENT DUE TO:
- AVGAS CONTAMINATION
- PROPANE TORCH INSTALLATION
- NON-AERODYNAMIC CONFIGURATION

SMALL FIREBALLS
- LIQUID JP-5 FUEL IN SMUDGE POTS

NO SIGNIFICANT FIRE DAMAGE TO FUSELAGE, STARBORD WING, AND INBOARD PORT
WING

FIGURE 2-35. SP-2 AIRCRAFT CRASH TEST NO. 4 PRELIMINARY RESULTS

Questions and answers following "Large-Scale Aircraft Crash Test of Antimisting Fuel"

Discussions:

Dr. Neiderhauser, Rohm and Hass: Your 0.3 percent fuel, would that include 0.3 percent polymer or 0.3 polymer plus a carrier fluid?

Mr. Klueg: The 0.3 percent fuel is the weight of a polymer itself. There is approximately six-tenths percent carrier fluid on top of that so that the total additive is on the order of 1 percent.

Dr. Carhart: Carhart, Naval Research Laboratory. What was the flash point, fire point, of the fuels that you used in the Naval Air Engineering Center (NAEC) crash test and what was the ambient temperatures? A very unrelated question just from curiosity on my part, what is considered to be the velocity of a crash survivable crash?

Mr. Klueg: The fuel temperature on that test was 75° F. The flash point of the fuel as delivered was on the order of 120° to 130° F, but neither it nor the fire point was measured at the time of test. The ambient temperature was roughly 35 degrees at test time. To answer the second question, there is a crash scenario study underway with Lockheed, Douglas, and Boeing, each having as one of the primary objectives of their study, to look at past accidents and identify the crash conditions that are considered to be survivable. We do feel that if we can protect at the landing velocities of today's aircraft, which are normally in the 120 to 140 knot range, we will do a good job providing protection.

Mr. Salmon: The ambient temperature of the wing spillage tests ranged over a period of time from summer to winter. The fan airstream raised the mixed air temperature 7° or 8° F above the ambient. We used 80 degree fuel as a base.

Mr. Franz: Mr. Franz, Pratt and Whitney Aircraft. Are the smudge pots an attempt to asimulate and localize the ignition sources under the wing?

Mr. Klueg: The smudge pots themselves were placed on the crash site only to insure that we had good exposure to fire. While there was no intent to have liquid fuel in those smudge pots, in some cases, particularly in the last tests, there was liquid determined by post-crash inspections. They are not really to asimulate actual crash conditions, but to give positive exposure of the fuel that is released to ignition sources. Again, we look at those crash tests as large-scale tests, not really as simulations of an actual full-scale crash.

Mr. Wittenberg: Art Wittenberg, Aviation Week and Space Technology. Did you try to test or indicate the significance of using fuel at the minimum effectiveness? What concentrations of the additive are required with 100° F flash point fuel?

Mr. Klueg: We did run a series of tests where we mixed 5 percent JP4 in with jet A to reduce the flash point and we found that pass/marginal boundary was shifted on the order of 10 to 15 knots to lower velocities. This would indicate that as we lower the flash point of the fuel we are going to lose fire protection. On the other hand, we can raise the additive concentration to compensate.

THE USE OF ANTIMISTING KEROSENE IN TURBOFAN JET ENGINES (AN EVALUATION PERFORMED BY PRATT AND WHITNEY AIRCRAFT GROUP, U.T.C.)

By

Harold W. Schmidt

NASA Lewis Research Center

I'm going to discuss the results of an evaluation of the use of antimisting kerosene in turbofan jet engines, performed by Pratt and Whitney for the Lewis Research Center and the FAA Techncial Center.

The antimisitng kerosene used in the experimental test program was the same as that tested for fire safety by the FAA; a jet-A base fuel, containing 3/10 percent by weight of FM-9 additive. The high shear resistance and resistance to misting and atomization that worked so good to reduce the crash fires that have been demonstrated by the FAA, also makes it difficult to start a fire in the engine (i.e., the fire resistance is an undesirable characteristic for fuel delivery systems, nozzle spray patterns and combustion). However, exposure to shear forces such as flow through feed systems tends to br~ak the polymeric molecules, reducing their average molecular weight, and con..i..ued shearing causes the fuel characteristics to revert back towards the properties of the base fuels; and very significantly this characteristic allows the possibility of conditioning or reverting the fuel to a level compatible to existing engine systems (figure 3-1).

An example of the effect of the 3/10 percent FM-9 in jet-A on the spray pattern of a JT8-D nozzle is shown in figure 3-2 on the right as compared to jet-A on the left; but notice particularly that partial degradation results in the improvement shown in the center, and illustrates the possibility that AMK could be accommodated.

The objectives of the Pratt and Whitney Program (figure 3-3) are: (1) to determine the feasibility of operating the JT8 engine with AMK; (2) to detemrine the degree of fuel degradation necessary for compatibility with existing fuel systems; (3) to determine the engine modification requirements; and (4) to determine the applicability of these resutls to other systems.

A brief outline of the program performed by Pratt and Whitney is shown in figure 3-4, broken down into seven basic tasks. The first task was to develop an understanding for handling the fuel; secondly it was necessary to determine general physical characteristics (task 2). The next 5 tasks, fuel injector performance, combustor performance, filter evaluation, pump and controller performance evaluation, were to evaluate the specific behavior of AMK in these components and to evaluate the function of the components with AMK. I would like to summarize briefly the results that were obtained.

In the first task, the JT8-D pump and an early model of an RAE degrader were evaluated for use as a degrader or processor. Since their performance was about the same, the JT8-D pump was used for degrading the fuel because it had a little higher capacity and it gave us an opportunity to get more testing data with AMK in that component. An example of the AMK shearing characteristics of the standard

JT8-D pump is shown on figure 3-5. The filtration ratio shown in the ordinate on the left is a ratio of the times for equal quantities of AMK and jet-A fueled to pass through a 17-micron screen and was used initially in this program as a measure of degradation. By measuring the filtration ratio as a function of the degree of degradation, it was found that after one pass through the pump, the fuel was degraded to a F.R. (filtration ratio) of 20; and after the second pass it has nearly reached the lowest level of 1.2, achieved after 3 passes through the pump. This was extended eventually out to 16 passes without further significant change in the filtration ratio. The reason for this was that the filtration ratio as a method of measuring degradation wasn't accurate below an F.R. of about 3 or 4; and tests later in the program indicated that most important range was a filter ratio between 2 and 1. By measuring the volumetric flow rate through a selected filter, (10 micron) and plotted against the delta-p (figure 3-6) notice that the volumetric flow rate becomes a very good measure of the level of degradation; and in addition, this procedure gives very excellent discrimination beyond the 3-pass degradation level shown on the previous slide, and the degradation level can now be expressed as a volumetric flow rate from 0.1 to 10. Also at the critical flow velocity, which occurs during the viscous turbulent flow transition, there was a tendency for gel formation. By staying below the so-called "critical velocity" gel formation, at least for the short term is no problem.

Now, I would like to discuss the physical characteristics; the heat transfer compatibility, thermal stability, water solubility and materials compatibility. As shown in figure 3-7, the unsheared antimisting kerosene heat transfer coefficient was about 1/2 of that indicated for jet-A. (Jet-A are the triangles clear to the left and the squares are the undegraded or unsheared AMK.) But with just 3 pass degradation, the coefficient approaches that of jet-A. Obviously the very large FM-9 molecules affects the fuel side heat transfer coefficient boundary layer. The 3-pass degradation was nearly enough to restore that. Long-term effects on the stability of the heat transfer coefficient through a given heat exchanger haven't been measured yet, but the thermal stability of the antimisting kerosene was found to be greater or better than that of jet-A.

The thermal stability of jet-A (the break point temperature) is about 230° to 245°; F and the break point temp of AMK is in the range of 260-275 or higher.

The water solubility limits of AMK are much more complex than for jet-A. AMK has a much higher water solubility than jet fuel, but excess water can precipitate the polymer and the formation of this precipitate is highly variable. It depends on the way the water is introduced, the temperature of water, and other factors. Therefore, the characteristics of this behavior with water is going to require more work to evaluate the limits of dissolved water over the possible operating conditions.

In the materials compatibility tests, there was some swelling of seal materials with FM-9; but soak tests with these materials for a period of 6 months at a room temperature and at elevated temperatures resulted in only minor swelling and it appears to be within tolerable limits. Copper strip test did indicate a little more reaction with FM-9 than with jet fuel, but after more than 100 hours of operation, the JT8-D pump was not affected; there were no measurable effects.

Let us talk now about the behavior of the components of AMK and also how AMK behaves in the components. In evaluation of the nozzle spray patterns, 3 different nozzles were tested to determine the affect of nozzle design on the spray pattern of AMK. Figure 3-8 illustrates the spray pattern with a standard P&W nozzle at

cruise conditions. Two figures 3-9 and 3-10 repeat the same conditions, with two successive nozzles. The emissions nozzle, figure 3-9, is a little better, but the same poor breakup with the undegraded AMK; in figure 3-10, the pressure blast nozzle (the Delevan injector) provides a little better breakup and even begins to break up the undegraded FM-9; but the significant thing there is that the greatest improvement was achieved by the degradation of the fuel to the 3-pass degradation level shown in the middle pictures. Therefore, the most practical way to accommodate the fuel is by degradation rather than redesign of these components.

Combustor performance included measurement of emissions and the altitude and restart capability of the nozzle. The tests, performed with AMK at 3-pass degradation level, had no measureable effect on the wall temperature. In the combustor emissions test (figure 3-11) comparing degraded AMK to jet-A, shows the oxide of nitrogen and the smoke to be the same for both 1 pass and 3 pass and for both the standard nozzle and the low-emissions nozzle. The hydrocarbon emission index for 3-pass AMK is about 70 percent higher than the jet-A and the carbon monoxide was 15 to 20 percent higher as shown at the bottom of figure 3-11. But these values are expected to be equal to jet-A when appropriate levels of degraded AMK are used.

The sea level ignition test shows again with 3-pass AMK, that a 9-can light for jet-A was achieved with jet-A at 500 pounds per hour as opposed to 750 pounds per hour for 3-pass AMK (figure 3-12). Also with the 3-pass, and I keep emphasizing this because it is a very minimal state of degradation, a relite altitude decrement of about 10,000 feet resulted. These two are expected to be normal with a high level of processing or degradation.

At this point in the program, 16-pass AMK or 16 passes of the fuel through the JT8-D pump was available to us, and so the rest of the tests were performed with the 16-pass material.

The extended duration filter test (figure 3-13) was made with the 16-pass fuel for a total of 1 hour, with the flow rates indicated and for the time shown for the 40-micron full-flow filter, and for 700 pounds (lbs) an hour for the wash-flow filter (a stainless steel mesh 40-micron filter) and there were no problems, no gel buildup and no clogging. Pump testing and calibration were normal, and as shown in figure 3-14, flow rates were higher with AMK for a given revolutions per minute (rpm) than they were with the jet fuel. Notice that at both 3500 and 2500 rpm, the top curve is the nondegraded AMK which gave the best performance, followed by the 3-pass and then the single point for jet A.

Because of the very close clearances and complex flow passages that exist in flow controllers (and these also include the primary filters in the fuel feed system), the fuel controller assembly is probably the most sensitive to AMK and will probably dictate the level of degradation for the engine. P&W performance tests with the JT8-D controller with 16-pass AMK was completed without measurable differences. Run-time was approximately 1 hour, single pass, followed by closed loop cycle tests, with no operational anomalies, no gel formation or buildup. (figure 3-15).

To summarize (figure 3-16), the short duration test of the JT8-D engine components, has shown that it is technically feasible to operate JT8-D engines with AMK fuel; but obviously there is much additional R&D required for practical considerations. The primary modification requirements for fan jet engines to accommodate AMK will be the addition of a fuel degrader (processor or reverter) before the fuel pump and

major filters. Data obtained with the JT8-D engine are applicable to other
engines because of the characteristic limiting parameters for AMK are the flow
velocity and the degradation level, and these are a function of the filter sizes
and clearance specifications of component parts of the fuel system. This means
that the level of degradation will be set to satisfy the requirements for each
engine as required.

In the follow-on program (figure 3-17), three major tests need to be completed
before complete engine tests can be run. First, long term effects on the fuel
system components; we need to be sure that residual, very high molecular weight
molecules that remain after shearing do not accumulate in the system over a long
period of time; and we have to establish a level of degradation required to pre-
clude gel formation, which is a function of AMK flow velocities and operational
temperatures. This has been done for the short time and we need to do this for the
long time. In other words, 7-10 pass degradation of AMK may be adequate for the
short term, but 12-16 pass or greater may be required for normal operational
periods.

Secondly, we have to establish the feasibility of providing the required degrada-
tion in 1 pass with an in-line degrader, this is quite a challenge. However, P&W
has already reviewed a number of concepts and devices, and they have already
achieved, in the laboratory, a degradation equivalent to 16-pass level degradation
in a 1 pass through this device. This will be used in the follow-on program and
they will evaluate the various concepts that would lead to design criteria for a
flight weight degrader. Finally, fuel icing and/or deicing tests must be made to
assure capability of accommodating dissolved or intrained water ice crystals.

BASE   JET A   JET FUEL

ADDITIVE - FM-9, A HIGH-MOLECULAR-WEIGHT POLYMERIC COMPOUND
        ● CONCENTRATION - IN THE RANGE OF C.3%

CHARACTERISTICS

    AMK HAS HICH SHEAR RESISTANCE

    RESiSTS MISTING AND ATOMIZATION

    EXPOSURE TO SHEAR FORCES SUCH AS FLOW THROUGH PIPES
    AND FITTINGS, PUMPS, AND FILTERS TEND TO BREAK THE
    POLYMERIC MOLECULES

    -   AVERAGE MOLECULAR WEIGHT IS REDUCED

    -   CONTINUED DEGRADATION CAUSES THE FUEL CHARACTERISTICS
        TO REVERT BACK TOWARDS THE PROPERTIES OF THE EASE FUEL

FIGURE 3-1.   ANTIMISTING KEROSENE CHARACTERISTICS

3-5

Jet A **Degraded FM-9** **Undegraded FM-9**

FIGURE 3-2.   SPRAY PATTERN WITH JT8D LOW EMISSION — IDLE

TO DETERMINE:

THE FEASIBILITY OF OPERATING THE JT8-D
ENGINE WITH FUEL CONTAINING FM-9

THE DEGREE OF AMK FUEL DEGRADATION NECESSARY
FOR COMPATIBILITY WITH EXISTING FUEL SYSTEM
DESIGNS

THE ENGINE MODIFICATION REQUIREMENTS (IF ANY)
FOR THE COMPATIBLE USE OF AMK/FM-9 IN THE
JT-8-D ENGINE

THE APPLICABILITY OF THE RESULTS TO OTHER ENGINES

FIGURE 3-3.   LEWIS RESEARCH CENTER AMK PROGRAM OBJECTIVES

1. FUEL HANDLING & QUALITY CONTROL
    o   FUEL ANALYSIS AND CHARACTERIZATION
    o   FUEL PROCESSING (DEGRADATION OR SHEARING)
        o   JT8D FUEL PUMP
        o   RAE DEGRADER
    o   DEGRADATION MEASUREMENTS

2. PHYSICAL CHARACTERISTICS:
    o   HEAT TRANSFER CAPABILITY   o   WATER SOLUBILITY
    o   THERMAL STABILITY   o   MATERIAL COMPATIBILITY

3. FUEL INJECTOR PERFORMANCE EVALUATION
    o   SPRAY QUALITY
        o   CURRENT PRESSURE ATOMIZING STANDARD NOZZLE
        o   LOW EMISSIONS AERATING NOZZLE
        o   EXTERNAL AIR ASSIT NOZZLE

4. COMBUSTOR PERFORMANCE EVALUATION
    o   COMBUSTION EFFICIENCY
        -   EMISSIONS (CO, HC, NO_x, SMOKE)
    o   RELIGHT TESTING
        -   ALTITUDE IGNITION
        -   SEA-LEVEL STARTING CAPABILITY

5. FILTER EVALUATION

6. PUMP PERFORMANCE EVALUATION

7. CONTROLLER PERFORMANCE EVALUATION

FIGURE 3-4.   PROGRAM APPROACH

JT8D fuel pump system
Number of passes vs ratio

Filtration ratio ~ $\dfrac{\text{AMK time (sec) thru 17 micron screen}}{\text{Jet "A" time (sec) thru 17 micron screen}}$

Conditions:
    Pump speed = 3000 rpm
    Fuel flow = 3500 pph
    Discharge pressure = 500 psig
    Sampled @ tank

F.R = 1.2

Number of passes
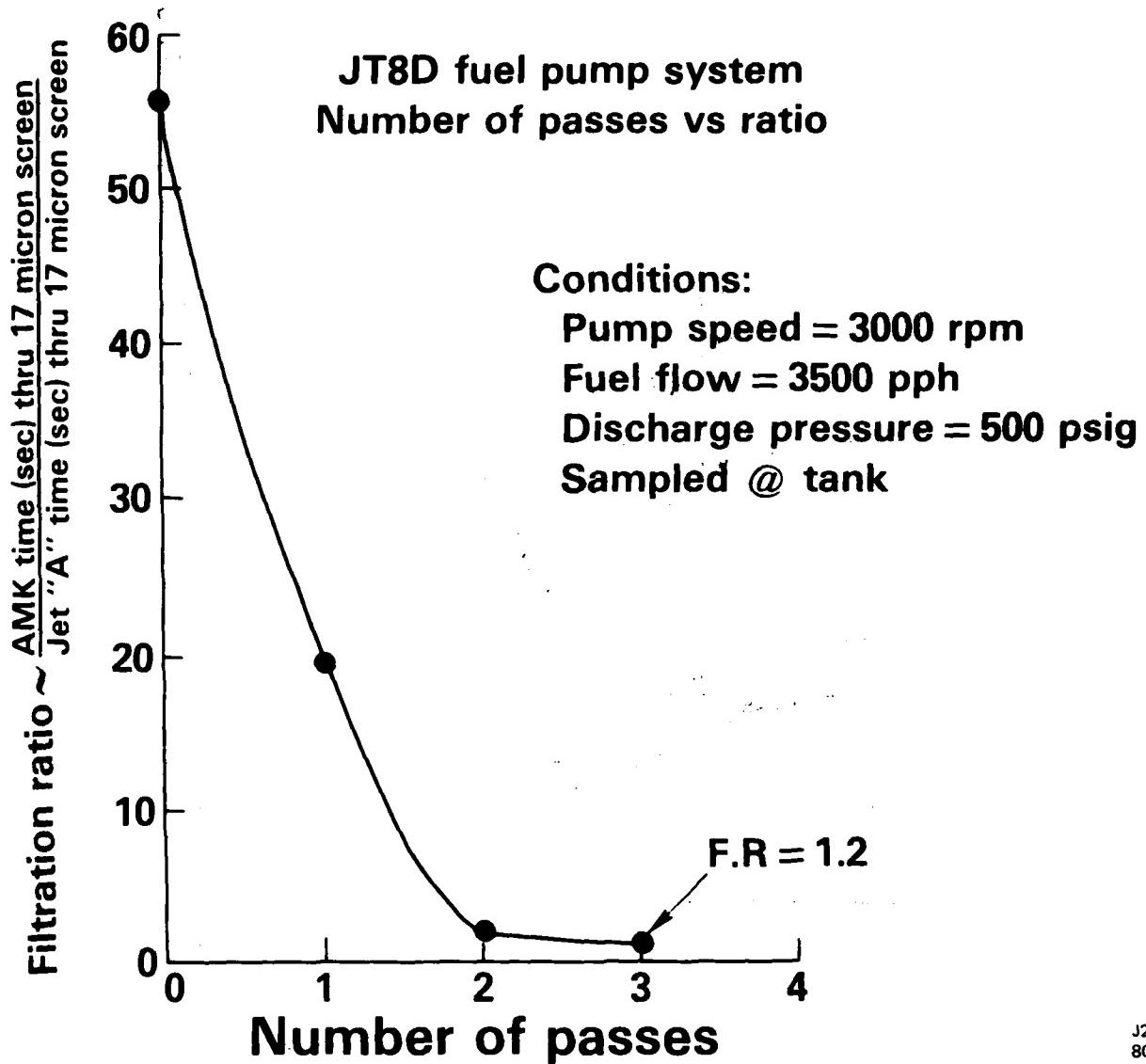
J227
802ʑ

FIGURE 3-5.   TYPICAL AMK SHEARING CHARACTERISTICS

3-9
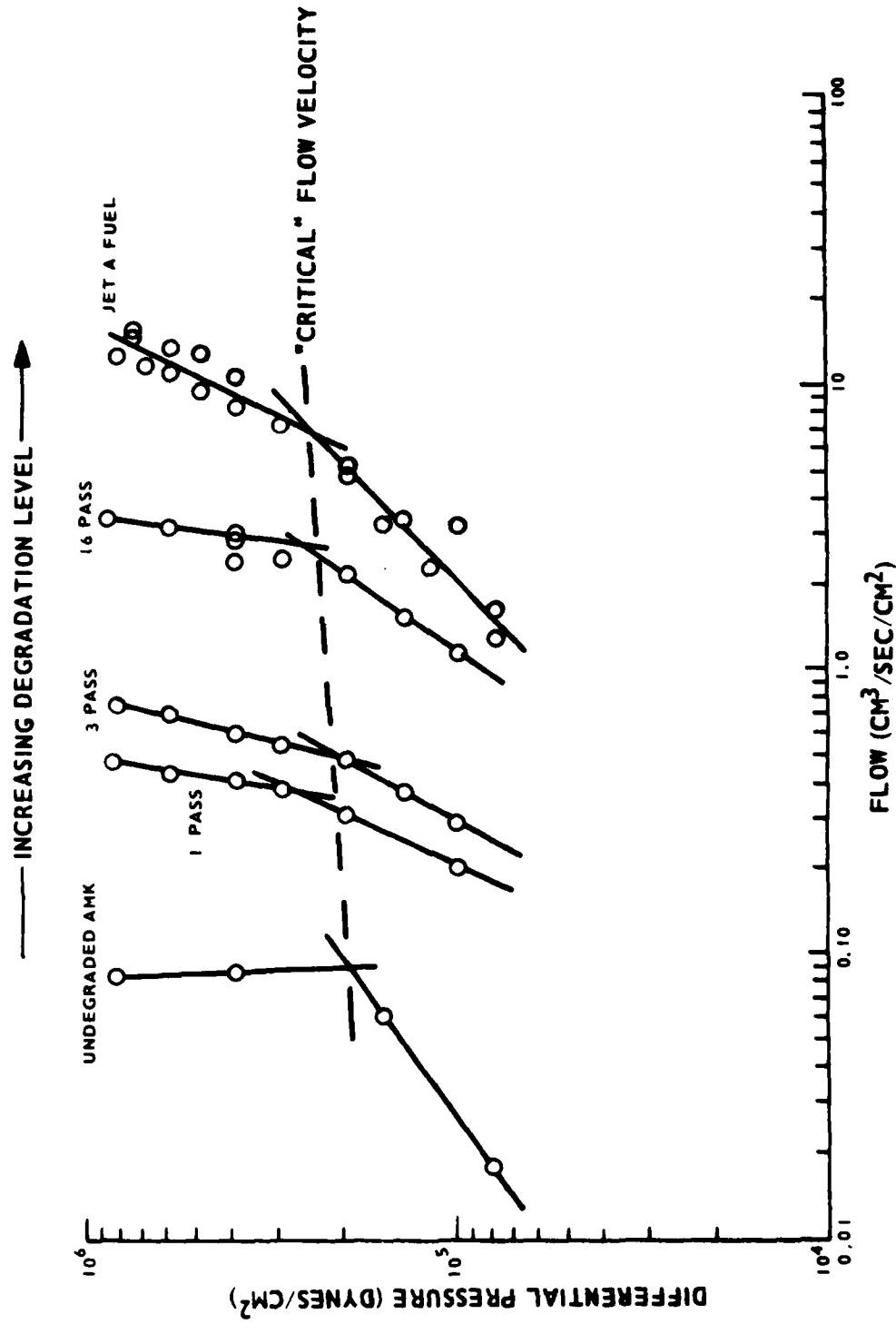
FIGURE 3-6. DEGRADATION LEVEL AND CRITICAL VELOCITY
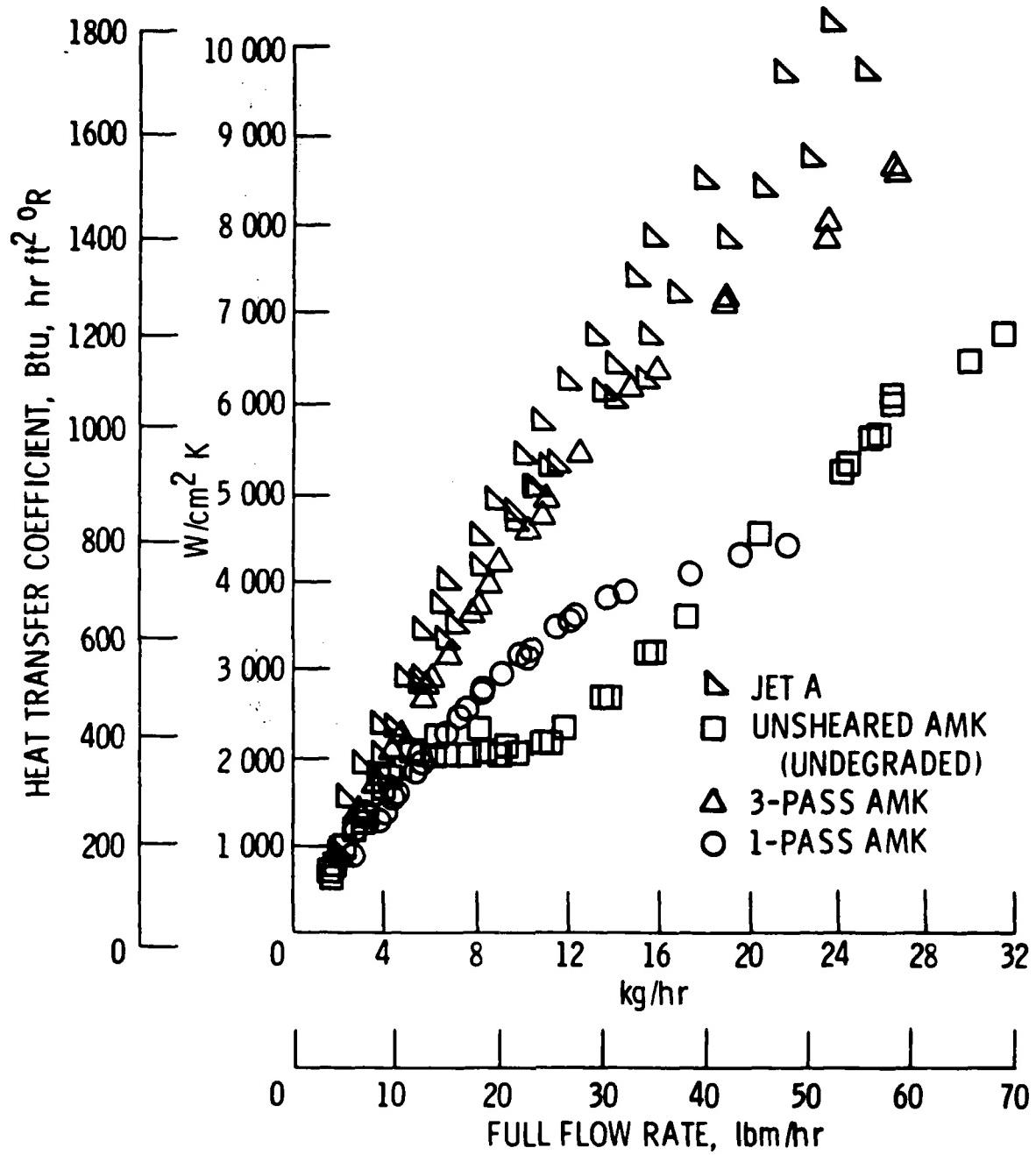
FIGURE 3-7.   EFFECT OF FM-9/AMK ON HEAT TRANSFER IN FUEL-OIL COOLER TUBES

Undegraded FM-9

Degraded FM-9
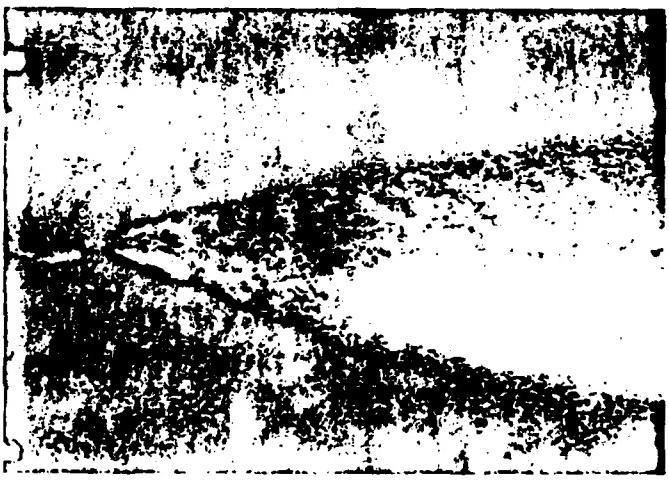
Jet A

FIGURE 3-8. SPRAY PATTERN WITH JT8D B/M – CRUISE

3-12

Jet A   Degraded FM-9   Undegraded FM-9

FIGURE 3-9. SPRAY PATTERN WITH JT8D LOW EMISSION INJECTOR — CRUISE

Undegraded FM-9

Degraded FM-9

Jet A

FIGURE 3-10. SPRAY PATTERN WITH AIR-BOOST INJECTOR — CRUISE

	B/M		L/E	
	1–PASS	3–PASS	1–PASS	3–PASS
NO$_x$	SAME	SAME	SAME	SAME
SMOKE	SAME	SAME	SAME	SAME

○ JET A

● 3–PASS AMK

NOMINAL RICH AND
LEAN IDLE

BILL–OF–MATERIAL COMBUSTOR
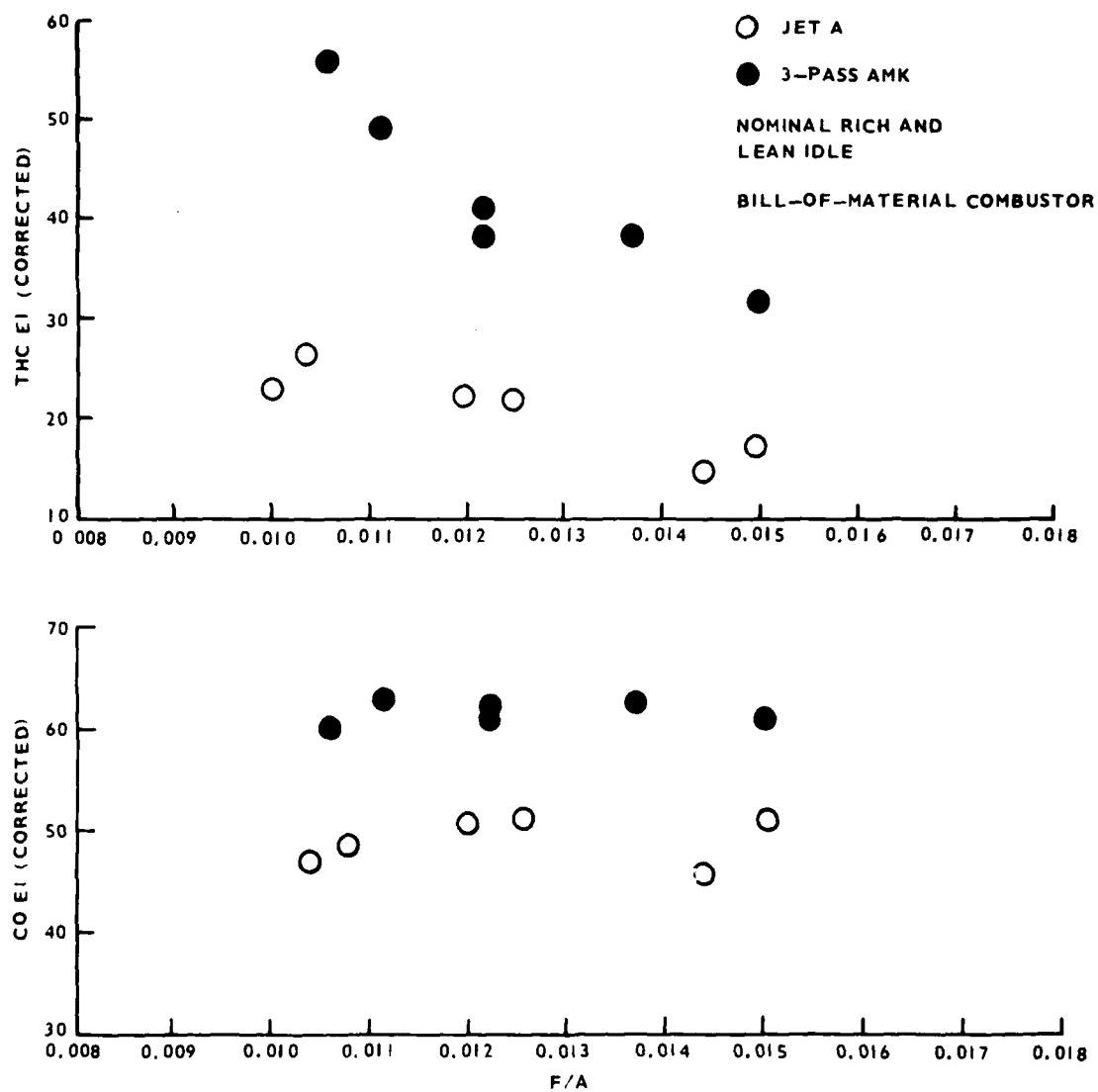
FIGURE 3-11. COMPARISON OF DEGRADED AMK TO JET A

3-15

LOW EMISSIONS BURNER

m_{AIR} (PPH) = 41,800

T FUEL = T4 = 59°F

FUEL	SYMBOL
JET A	○
3—PASS	●

(LBM/HR)

800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0

0   1   2   3   4   5   6   7   8   9

NUMBER OF BURNER CAN LIGHTS
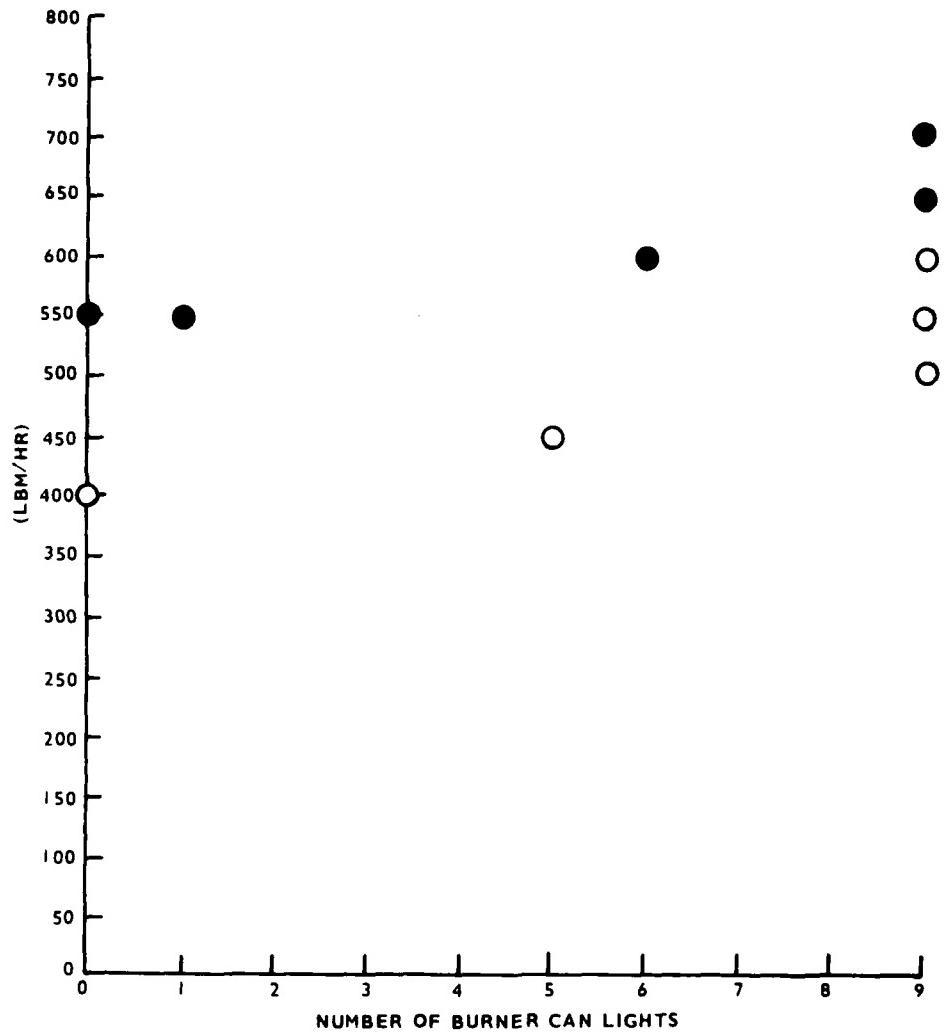
FIGURE 3-12.   SEA LEVEL IGNITION

16 - PASS (FR-1.2) AMK FOR ONE HOUR

TIME	FUEL PUMP 40 MICRON FUEL CONTROL INLET COARSE FILTER FLOW (LBm/HR)	FUEL CONTROL WASH FILTER FLOW (LBm/HR)
30	3000	
10	6000	700 for
20	2800	1 hour

No differential pressure buildup was observed on any of the filters. Also, the FR's sampled downstream and upstream of the JT8 filters were essentially the same.

FIGURE 3-13.   FUEL PUMP — CONTROL EXTENDED DURATION FILTER TEST
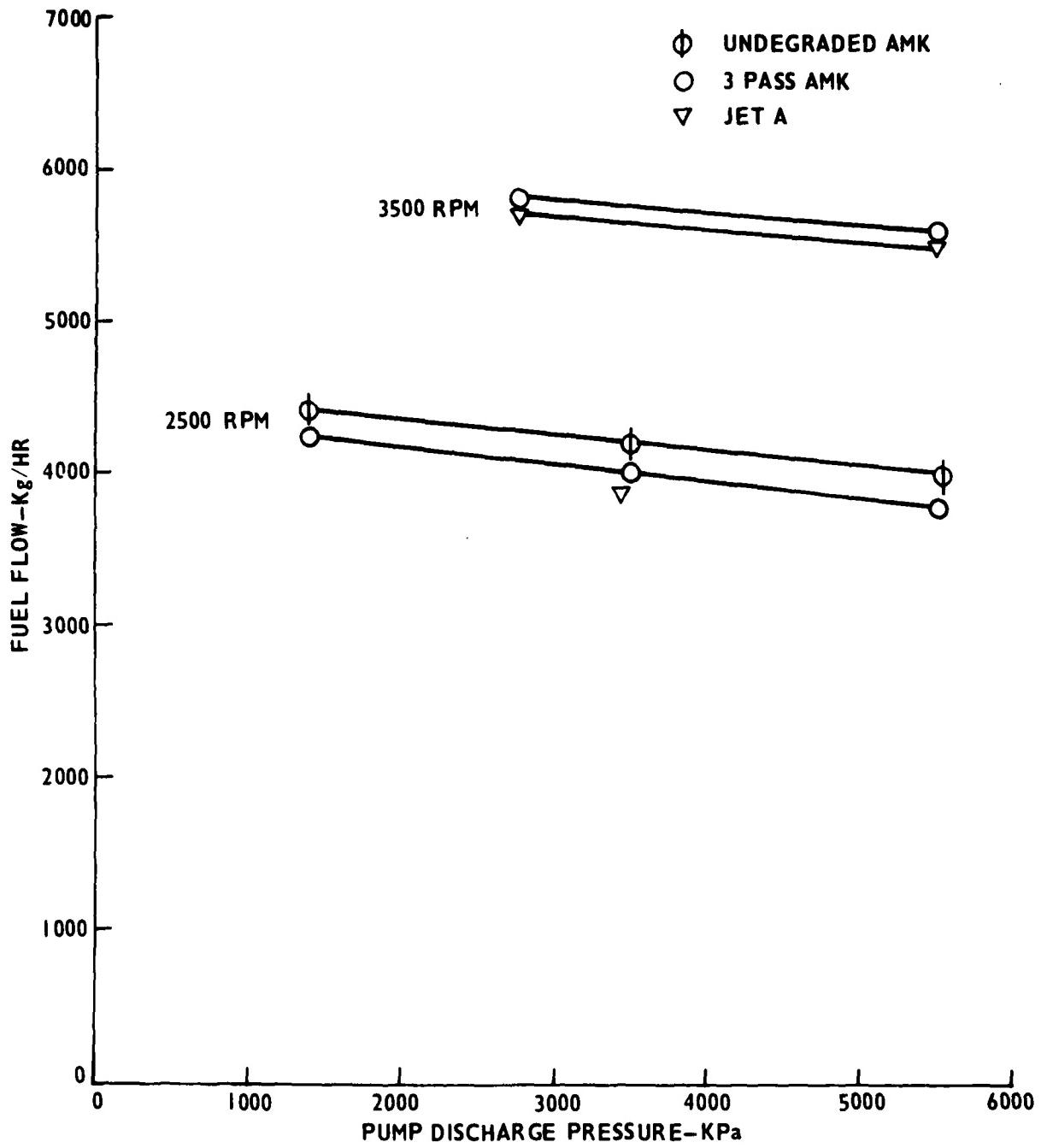
FIGURE 3-14.   FUEL PUMP PERFORMANCE

3-18

PERFORMANCE TESTS WITH 16 PASS (FILTER RATIO APPROX 1.16)
COMPLETED WITHOUT MEASUREABLE DIFFERENCES. (RUN TIME
APPROXIMATELY 1 HOUR, SINGLE PASS).

EIGHT HOUR CLOSED LOOP CYCLE TEST WITH 16 PASS AMK
WAS NORMAL

FIGURE 3-15.   FUEL CONTROLLER TESTS

RESULTS AND CONCLUSIONS

SHORT DURATION TESTS OF JT8-D ENGINE COMPONENTS HAVE
SHOWN THAT:

- IT IS TECHNICALLY FEASIBLE TO OPERATE JT8-D
  ENGINES WITH 0.3% FM-9/AMK FUEL (ADDITIONAL R&D
 REQUIRED FOR PRACTICLE CONSIDERATION).

- THE PRIMARY MODIFICATION REQUIREMENTS FOR FANJET
  ENGINES TO ACCOMMODATE FM-9/AMK WILL BE THE
  ADDITION OF A FUEL DEGRADER (PROCESSOR) (REVERTER)
  BEFORE THE FUEL PUMP - TO PROVIDE THE SELECTED LEVEL
  OF MOLECULAR WEIGHT DEGRADATION.

- DATA OBTAINED WITH THE JT8-D ARE APPLICABLE TO
  OTHER ENGINES, BECAUSE THE CHARACTERISTIC
  LIMITING PARAMETERS OF AMK ARE THE CRITICAL FLOW
  VELOCITY AND THE DEGRADATION LEVEL, AND THESE ARE
  A FUNCTION OF FILTER MESH SIZES AND CLEARANCE
  SPECIFICATIONS OF COMPONENT PARTS.

FIGURE 3-16. AMK PROGRAM STATUS

- LONG TERM AFFECTS TESTS ON FUEL SYSTEM COMPONENTS

  - ESTABLISH THE LEVEL OF MOLECULAR DEGRADATION
    REQUIRED TO PRECLUDE GELL FORMATION (F) AMK
    FLOW VELOCITIES AND OPERATIONAL TEMPERATURES

- ESTABLISH THE FEASIBILITY OF PROVIDING THE REQUIRED
  LEVEL OF AMK DEGRADATION IN A ONE-PASS, IN-LINE DEGRADER

- PERFORM FUEL DE-ICING TESTS TO ASSURE CAPABILITY OF
  ACCOMMODATING DISSOLVED OR ENTRAINED WATER

FIGURE 3-17.   FOLLOW-ON PROGRAM

Questions and answers following "The Use of Antimisting Fuel in Turbofan Engines"

Discussions:

Mr. Henry: Sy Henry, Dupont. When you spoke of the compatibility test work of FM-9, were you talking about the polymer alone or the polymer plus the carrier fluid?

Mr. Schmidt: That was the jet A fuel mixture with the carrier fluid present.

Mr. Moore: Moore, Shell Chemical. Would you confirm the water sensitivity precipitated the polymer or did it precipitate the glycol? Generally, water in hydrocarbons containing glycol knocks out the glycol into the water layer. I was curious whether it was confirmed that the polymer ended up in the water glycol layer. On the subject of does a polymer break, the answer is yes, it does. When it breaks it forms free radicals and the free radicals initiate further polymerization. I wonder if you ever thought of this in the sense of gel formation, because gel requires three dimensional polymer configuration.

Mr. Schmidt: My personal opinion is that gel forms when polymerization occurs as a result of the shear stress, such as when the fluid is accelerated over a very short path length, as in a filtration process.

Mr. Bammer: Bammer, Westland Helicopter. The degrader, if effective, will it be positioned downstream of the engine pressure pump?

Mr. Schmidt: The degrader wouldn't have to be downstream or upstream of the fuel pump as such. It would depend on how your system is designed.

Mr. Bammer: Would the fuel degrader be satisfactory in a low pressure part of the system?

Mr. Schmidt: The fuel degrader probably will be a pressure device. It could be on either side of the existing pumps or possibly take the place of it. The main requirement is to go through the degradation process before any of the filters and certainly before any of the critical components. The pump can handle undegraded fuel very nicely as you saw in the pump test results. In fact, it works better in the pump than does jet A from these limited tests. Another degrader downstream of the pump would appear to be acceptable to apply the stress on the fuel to shear the molecules. I'm not so sure whether I have answered your question, but I don't see it matters whether it's upstream or downstream of the main pump.

Unidentified Speaker: Regarding the so called improvement and not to be misled on what we felt was occurring, the pump is a positive displacement device. We feel that the improved performance on the undegraded fuel was due to the clearance in the pump and the lubricating passages in the pump being perhaps plugged with slight gel formation, but this pump was not sensitive to it. Don't be misled by the fact that other pumps running at the conditions of the AD pump would not be sensitive to losing this lubrication flow within it. We feel the definite increase in the so-called crank flow performance was due to the reduction in the bearing lubrication flow.

Mr. Franz: What are the power requirements of the degrader? How much will you get in a one pass in-line job?

Mr. Schmidt: The Pratt and Whitney pump was not intended to be used as a degrader. Because of the way it was used, it was possible to measure the difference in the energy input in the degrading versus to the pumping fluid. The amount of energy that goes into actual degradation may be very small; if you are degrading it by pumping.

Mr. Franz: The high pressure reduction across the valve was probably doing the degrading when we used it in our system.

Mr. Schmidt: I suggested earlier that it might be worth while to consider having a degrader and pump as the same device; the additional energy required for the degradation would be negligible.

THE DEVELOPMENT OF ICI'S FM-9 ANTIMISTING AVIATION FUEL

By

J. W. Mossel, ICI Americas, Inc

F. A. Waite, ICI Limited

INTRODUCTION

The antimisting concept is rather simple and straightforward — the objective is to reduce fuel misting under stress conditions, thereby avoiding the mist environment and resulting fireball characteristic of many impact survivable aircraft crashes. To reduce this concept to practice is extremely difficult, however, it brings into play a great many facets of chemistry, physics, combustion technology, fuel management, and propulsion.

If we were to design an AMK additive, we would look for these specific properties:

- simple, straightforward chemistry
- good solubility in aviation fuel
- effective fire reduction
- not impair combustion efficiency
- minimum effect on fuel management
- nonpolluting and nontoxic
- easy to transport
- inexpensive

Having given these properties, I will leave it to you if you wish to design a proper product to fit these parameters.

COOPERATIVE RESEARCH PROGRAM WITH RAE.

Allow me now to give some histroy on the extensive ICI research program. We did not start with antimisting as the preferred property to reduce post-crash fires. When the RAE first approached ICI in 1967, it was proposed that the RAE sponsor a research program into the aspects of gelling fuels to enhance aircraft safety. It soon became apparent that the most important factor in postcrash fuel fires was the presence of fuel mist and that this was especially true in the case of high flash-point fuels like jet A which in other respects are difficult to ignite. We believe that if aviation kerosene could be modified to reduce this tendency to form fine mists, then there would be a reduction in the incidence of fuel ignition under postcrash conditions. If the crash impact is survivable, lives could be saved. An extensive research effort was started.

THE ANTIMISTING EFFECT.

Many automotive paints are pigmented solutions of acrylic polymers. Sometimes when the paint fails to atomize, the effect is associated with the acrylic polymer having a higher molecular weight than normal. At the time, 1968, the exact mechanism of this phenomenon was not known. Trying to understand this mechanism appeared to be a suitable starting point from which to investigate mist suppression.

4-1

Polyisobutylene (PIB) is soluble in aviation kerosene and is commercially available in a range of molecular weights. We made up PIB solutions in aviation kerosene and a simple atomizing test correlated the results to molecular weight and the concentration of PIB in solution. Atomization could be suppressed by dissolving a high molecular weight polymer in aviation fuel, provided the concentration was above a critical level. Let us define critical level as that concentration showing the first signs of visco-elasticity, that point at which flow of the liquid is not simply related to the stress applied. At that critical concentration, the polymer chains started to become entangled. It was not surprising that the higher the molecular weight, the lower the value of this critical concentration.

Many polymer solvent systems were evaluated and this phenomenon was demonstrated to be generally true. Having established the conditions for inhibiting the tendency of a liquid to form fine droplets — i.e., misting, let us now examine the mechanism of this phenomenon. We call this the entanglement concept.

ENTANGLEMENT CONCEPT.

Figure 4-1 (A&B) are graphic representations of polymer solutions — figure A shows polymer below the critical concentration and figure B above the critical concentration. It must be remembered that the chains are continually writhing and moving relative to each other. Nevertheless, it can be seen that bulk solution A can flow and be split up into droplets without chains being broken or disentangled. On the other hand, to break up bulk solution B into droplets chains will either have to be broken or disentangled. Time is required for chains to disentangle. When sufficient time is available for relaxation, the chains disentangle and resistance to flow is low. If time is short and deformation is rapid as encountered in an atomizing situation, the chains do not have time to disentangle and will offer significant resistance to atomizing — resistance to misting — antimisting.

Thus, solutions of entangled high molecular weight polymers behave, under certain conditions, as transient, tough elastic gels and under other conditions, as low viscosity liquids.

FM-3 RESEARCH PROGRAM.

In AMK research, mist reduction is only desirable as a function of fire reduction. This was examined next. Resistance to ignition was readily demonstrated, provided that fuel was at the relatively high flashpoint and the polymer concentration was higher than the critical concentration of entanglement. On the basis of these results, a separate, extensive research effort focused on PIB and finally the best candidate with a molecular weight of 4.5 million, was designated FM-3 and submitted to the RAE for further evaluation.

It should be stressed that a few key tests were selected and these were only expanded in number and severity when the performance of the additive was deemed to warrant a fuller investigation. For FM-3, the test selected was relative to fire suppression using the rocket sled test devised by the RAE and other tests such as pipe flow, pumping, and combustion.

The RAE's investigation of FM-3 clearly demonstrated the potential benefit of mist suppression but it also highlighted certain key problems.

FM-3 would produce mist suppression at concentrations as low as 0.1 percent but to be sure of passing the rocket sled test concentrations of up to 1.0 percent were needed. As the severity of the fire test increased, the concentration had to be raised to be assured of passing. (This effect is related to the forced disentanglement of the polymer chains.)

The pump efficiency of FM-3 modified fuel in a typical aircraft centrifugal pump was low, relative to that of unmodified kerosene and at low temperatures (-20 to -40° C) the modified fuel was virtually unpumpable.

All high molecular weight polymers are degraded, that is, are broken down into lower molecuar weight fragments, when these solutions are subjected to mechanical stress, such as those encountered in pumps and in filters. With these effects in mind, although it may be desirable to incorporate the additive into the fuel at the refinery, it seems an impossible task to deliver such fuels into the aircraft fuel tanks while retaining the antimisting property. Our view was, and continues to be, that the additive must be incorporated into the fuel at the airport.

FM-5 RESEARCH PROGRAM.

Besides PIB, we began to examine a range of new fuel modifiers with the objective to improve the properties of the modified fuel, select less expensive and more readily available raw materials and continue testing to learn more about the behavior of additives in fuel. A large number of high molecular weight ethylene/ propylene co-polymers were synthesized and evaluated. One of these we designated as FM-5.

The main advantage of FM-5 over FM-3 was the concentration at which fire suppression could be achieved as demonstrated by the rocket sled tests at RAE. Under certain conditions as little as 0.1 percent of FM-5 was needed. Unfortunately, this effect was extremely temperature sensitive. This temperature sensitivity was also reflected in pipe flow and pump performance. At about -10° C the polymer came out of solution forming an intractable gel. Much effort was expended in trying to overcome this temperature sensitivity but without success. Nevertheless, the behavior of FM-5 did provide a clue to further progress. The enhanced fire suppression was related to the presence of strong polymer association. This polymer/ polymer adhesion is, roughly speaking, the equivalent to molecular friction. (It is much easier to disentangle spaghetti than string that is entangled. In the former, friction is low; the latter, friction is high).

FM-4 RESEARCH PROGRAM.

We looked at introducing associative groups into the polymer chains —— one of these became FM-4. Although its fire reduction concentration was not as good as FM-5, FM-4 at 0.3 percent was by far the best additive yet examined. Not only would it pass the rocket sled tests in quite severe configurations, but in a wide variety of flow conditions it was less sensitive to temperature even than FM-3. However, its low temperature pump efficiency was still unacceptable. Nevertheless, we were now willing to face another obstacle — how to incorporate or blend the additive into fuel.

FM-4, in common with FM-3 and FM-5 and the majority of other polymers, are soluble in aviation fuel but are rubber-type products at normal temperatures. In large form these dissolve slowly, taking weeks. In small pieces, even cryogenically

4-3

milling these into small particles sizes, the process is too inconvenient, expensive and cumbersome to be considered. We set ourselves the task of looking for additives which could be produced in fine powder form and would not form lumps when stored. We now looked for raw materials which would produce polymers still soluble in aviation fuel but which were hard and brittle at ambient temperatures.

FM-6, FM-7, AND FM-8 RESEARCG PROGRAM.

A new series of polymers were synthesized; resulting in FM-6, FM-7, and FM-8. FM-6 was abandoned in favor of FM-7 because of reproducibility problems. And FM-7, which gave less effective fire suppression, was abandoned in favor of FM-8 which was, at least, as good as FM-4 in this respect. Having achieved an additive in the form which provided a potential solution to the blending problem, because it was in powder form, attention was turned once again to the remaining problem of low-temperatue pumping.

FM-9 RESEARCH PROGRAM.

Having gained more experience and some understanding of what we were looking for, a variety of FM-8 types were made with the view to reducing its temperature sensitivity while maintaining its fire suppression activity and solid, brittle property. The outcome of this study was FM-9, which is not only produced in fine particulate form, but at 0.3 percent in fuel, is also as good as FM-8 with respect to fire suppression. Moreover, the modified fuel pumped with an efficiency of 70-80 percent over that of aviation fuel at ambient temperatures and was independent of temperatures down to $-40°$ C. Furthermore, over the whole temperature range of $-40°$ to $+35°$ C, the viscosity of the modified fuel was very low indeed and in mild flow conditions, it was qualitatively indistinguishable from ordinary aviation fuel.

Although FM-9 can be provided in the form of fine powder, it will only dissolve in fuel when the fuel is heated. Heating fuel is obviously not practical, so we applied the dispersion technique using a carrier fluid to form a paste or slurry of FM-9. This readily dissolved in aviation fuel at ordinary temperatures.

All along, while we are attempting to impart an antimisting property to aviation fuel to reduce postcrash fires, it must be remembered that atomization or misting of the fuel must occur in order to support combustion in aircraft engines.

These two properties are mutually exclusive and yet the fuel must be able to render each property on demand as conditions warrant.

To accomplish this, the modified fuel is maintained in its antimisting state and only just prior to going to the engine is the antimisting property taken out of the fuel by degradation.

As mentioned before, high molecular weight polymers, including FM-9 are degraded when their solutions are subjected to mechanical stress. While further research under the FAA AMK program is directed to this, adequate degradation of FM-9 has already been demonstrated using small mechanical devices which vigorously agitate the fuel.

It will also be recalled that in order to avoid unwanted degradation in pumps and filters in the fuel distribution system, the additive has to be added at the aircraft refueling site. At present, it is anticipated that FM-9 will be supplied as a high concentrate slurry which, when blended with aviation fuel at the airport, rapidly dissolves generating the antimisting effect. Further work in this area is another research task which the FAA AMK program is addressing.

To date, the FM-9 development seems to have answered the questions, at least in principle, of low concentration effectiveness, pumpability, effective use over a wide range of temperatures, blending, and fuel handling.

The FAA AMK program is designed to cover all aspects of using modified fuel. It is difficult to imagine that no specific problems or obstacles will be encountered in the future. Indeed that is the objective of the AMK program — to search these out and by combining the best efforts of government and industry, to solve these. However, at present no insurmountable obstacles have been encountered.

Just as we have made progress in the past, ICI anticipates continuing its efforts in research, product development, and engineering facilities planning. We anticipate making product improvement in the future just as we have in the past.

In view of the potential market, we anticipate that other companies will provide candidate samples. We welcome such competition. Before ICI makes significant capital investment, we want to be certain that our product offers good AMK properties so that lives can be saved.

B

A

FIGURE 4-1. REPRESENTATION OF POLYMER SOLUTIONS
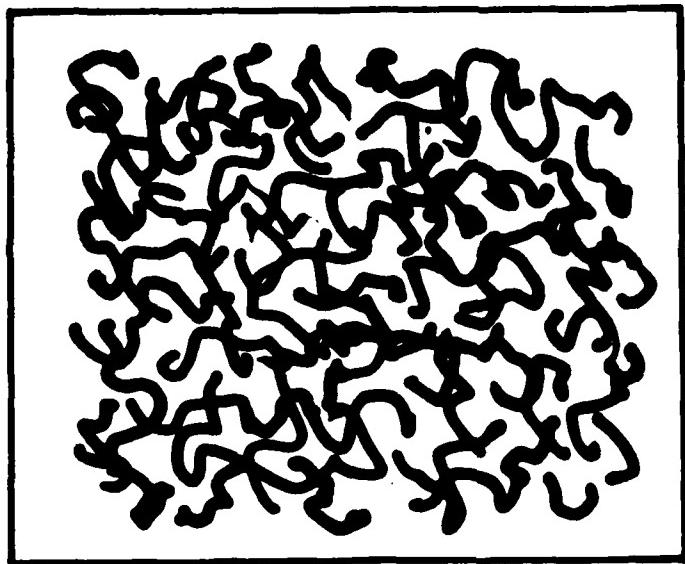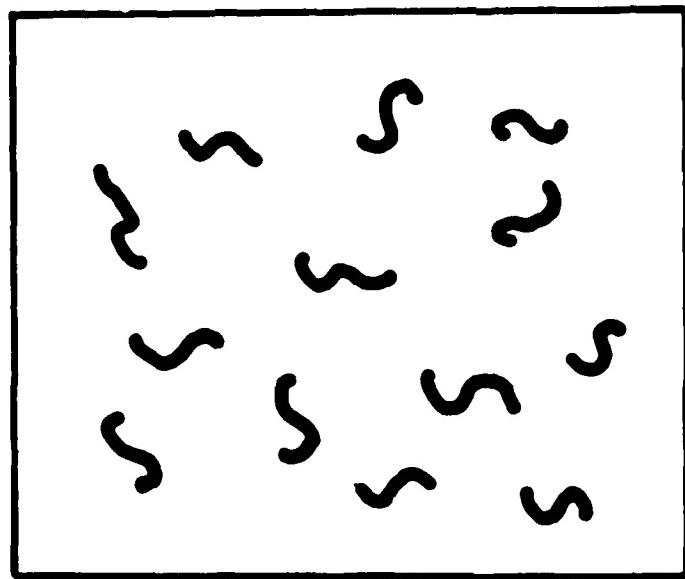
Questions and answers following "The Development of ICI's FM-9 Antimisting Aviation Fuel"

Discussions:

Mr. Niederhousen: What is your projection of cost, assuming that it's mandated, for all of the commercial users?

Mr. Mossel: It is an extremely difficult question to answer at the present time. We've been asked to look at economy evaluations to asist in the cost benefit analysis. In doing this, we have given some marginal indication, which is basically in the range of 5 percent added to the cost of the fuel. Keep in mind, this is literally off the top of our heads. We have had no in-depth engineering studies.

Mr. Peat: Have you given any consideration to the heat transfer? There are a number of things that the fuel is expected to do in the engine before you burn it. One of the things the fuel does, is to absorb heat from the oil. If we are going to lose this heat transfer property, particulary when using low.pressure heat exchangers, is there anything that can be done to restore the heat transfer poperty?

Mr. Mossel: Certainly, that is still being investigated, but it is really outside of our area of the chemical industries to address that question. The FAA and its subcontractors are looking into these areas. If there are questions that come up, we will have to address them as they surface.

Mr. Westfield: We feel, as the level of degradation increases, the problems with the heat transfer decreased. Assuming that we do achieve the requisite degradation level, we may solve the other problem at the same time.

Mr. Peat: Can anything be done chemically as opposed to mechanically? You see, there is a question of where you put your degrader. The pressures involved determine where your heat exchangers are. Thus to avoid the lots of changes, could you restore this fuel property back by a chemical means?

Mr. Mossel: I understand what you're saying. I can't address that particular question. Certainly, let's say we'll endeavor, wherever we can, to solve these means chemically rather than mechanically. It certainly is more cost effective.

Mr. Sarohia, Jet Propulsion Laboratory: Does ICI see any problems with FM-9 as a antimisting fuel additive?

Mr. Mossel: We will continue to work on all of these areas of our technology and hopefully improve as we go along. We don't see any problems with FM-9 as an additive. We wouldn't be here at the present time devoting our energies and activities to it. If we felt there was a major problem we'd be the first one to tell the FAA. We would withdraw our particular candidate and leave the field open to others, if such problems occur. Certainly, as I said in my talk, before anybody at ICI puts in significant capital investment, we have to be certain that the antimisting properties that were given to the fuel were the best that can be given. If this happens to come from a competitor, I would want to know about it today rather than next week when we might have sunk a lot of money into the ground.

CRYOGENIC BLENDING POLYMER ADDITIVES IN FUEL

INTRODUCTION

The FAA's Engineering and Development Plan for Antimisting Fuels has, as one of five critical issues in the commercialization of antimisting fuel, the feasibility of blending the fuel at the aircraft fueling point (figure 5-1). General Technologies Applications (GTA) has a proprietary process for rapidly dissolving high molecular weight polymers in compatible liquids which we believe can be adapted for blending certain antimisting additives directly into aircraft fuel tanks. We have completed the laboratory work for a contract with the FAA under which we applied this process to the blending of two different types of antimisting additives with jet A. I will describe the GTA process, give the results of our work for the FAA, and suggest what we believe to be significant of this work for the commercialization of antimisting fuels.

DESCRIPTION OF THE GTA PROCESS.

The GTA blending process (figure 5-2) utilizes cryofracturing to produce active surfaces in fractured polymer particles. The active surfaces interact with the solvent, resulting in very rapid solution. The active surfaces can be preserved by maintaining the particles in a cold, inert atmosphere. While some molecular bond breaking is required for the production of the active surfaces, degradation of the polymer is minimal.

The first use f the GTA process was in connection with pipeline drag reduction studies. A l of a viscosity average molecular weight of 4.6 million was blended with kerosene in concentrations from 1 to 25 percent. Solvation time of under 1 minute was confirmed by drag reduction tests using newly blended samples of a 1 percent concentration. Recently, under a contract with the FAA the process was used to blend PIB of viscosity average molecular weight of 5.6 million in jet A.

GTA'S CONTRACT WITH THE FAA.

The GTA process was developed for on-site blending of pipeline drag reduction additives. It was this background that brought us into the antimisting area (figure 5-3). There are a number of scientists who believe that there are significant correlations between the drag reduction and antimisting phenomena. It was a suggestion by one such scientist that led us to the FAA last May. We discovered that on-site antimisting fuels blending was an unresolved and critical issue in the antimisting fuels program.

In late August, we began a contract (figure 5-4) with the FAA to produce blended antimisting fuels for testing at the FAA Technical Center. We were to blend two types of polymers in two phases: first, a number of 5-gallon samples were to be produced for testing in several subscale test apparatuses; second, sufficient amounts of antimisting fuels were to be produced for testing in the Technical Center's wing spillage test apparatus. The second phase of the contract was to be triggered by evidence in the subscale tests that the blended fuels had antimisting behavior. The two polymers for blending were to be selected by the FAA.

The two additives selected were Imperial Chemical Industries FM-9 and BASF's Oppanol B-230 (figure 5-5). FM-9 was chosen because it was the additive being

5-1

investigated by the FAA in their antimisting fuel program and because the point of fuel blending had not yet been demonstrated satisfactorily. FM-9 is a flow induced gelling type antimisting additive. Oppanol B-230 was chosen primarily because of GTA's experience with high molecular weight PIB in its drag reduction work. It was also considered to be representative of a class of amorphous polyolefins which exhibit significant viscoelastic properties, particularly at the higher molecular weights. Viscoelasticity in a liquid is known to suppress it misting behavior. Oppanol B-230 had the highest molecular weight of any PIB available.

FAA intended that GTA work initially with FM-9. However, it was not made available during the contract period and GTA was directed to proceed with the B-230 blending.

The objective of the first phase of the contract was to provide sufficient quantities of fuel blends for subscale testing at the FAA Technical Center facilities. For this purpose, GTA fabricated a simple batch blending system in which the cryofractured polymer particles fall directly into a spray of neat jet A fuel. The fuel pump and cryomill were coordinated to produce the desired concentrations. A spigot in the collection tank allowed samples of the blended fuel to be taken immediately upon completion of blending. The feed rate was dictated by the pump and mill capacities. For a 0.3 percent concentration, the blending rate was approximately 4 gallons per minute.

The primary design criterion was to create a batch blending system from which a fuel sample could be taken for testing within seconds after the antimisting polymer was introduced into the jet A.

The blending operation was to be carried out at GTA's facilities in Gaithersburg, Maryland. Since the FAA subscale testing facilities are located in Atlantic City, New Jersey, it was necessary to develop test procedures at the Gaithersburg laboratory for determining the effectiveness of the blending operation immediately after blending.

For this purpose, GTA used two analytical tests (figure 5-6). A Brookfield viscometer was to be used for determining viscosity and concentration of the blended fuel from a calibration curve. An impulse sprayer was to be used to test misting behavior. When used with neat jet A fuel, the sprayer produces a fine mist. Both the Brookfield viscometer and the impulse sprayer can provide test results within a few seconds after the fuel samples are obtained.

In addition, a team from the FAA Technical Center assigned to observe the GTA blending operation brought a rheology pump test apparatus which was to be used to determine the antimisting properties of the blended fuels (figure 5-7).

GTA prepared a total of 75 gallons of B-230/jet A samples ranging in concentration from 0.1 to 0.3 percent for testing by the FAA. The FAA observer team was present for the preparation of one sample. GTA was requested to blend a 0.3 percent concentration (figure 5-8). A 7-gallon sample was blended in approximately 2 minutes. Samples were taken immediately after the completion of the blending operation for test in the Brookfield viscometer, the impulse sprayer and the rheology pump apparatus. The Brookfield viscometer indicated a concentration of 0.28 percent. Subsequent viscometer readings made at 20-minute intervals over the next 4 hours indicated no appreciable change in concentration. The impulse spray

test was conducted approximately 3 minutes after the completion of the blending operation. It produced a long thin stream of fuel in contrast to the fine mist characteristic of neat jet A. The FAA, using the rheology pump apparatus, determined that the B-230/jet A sample would demonstrate significant antimisting behavior. The test results indicated that Oppanol B-230 was put into solution in jet A in under 2 minutes, and that the fuel mix had significant antimisting behavior once in solution.

The full range of B-230/jet A samples blended by GTA for the FAA were tested in the FAA's subscale flammability apparatus. These tests confirmed the earlier conclusion that B-230/jet A fuels would have significant antimisting behavior (figure 5-9). By way of comparison in this test apparatus, a 0.15 percent concentration of B-230 in jet A was equivalent in antimisting performance to a 0.3 percent concentration of FM-9 in jet A.

It was determined by the FAA that the second phase of the contract, calling for the preparation of blended fuels for use in the FAA's wing spillage test, would not be conducted with B-230.

The FAA then obtained FM-9 for blending by GTA. A new second phase was initiated under which GTA would try its blending process with a fine FM-9 powder and a slurry of FM-9 and its carrier fluid. Since the GTA process requires the breaking of some molecular bonds, an attempt was made to develop procedures for putting the powder and slurry into a form which would make this possible. After procedures had been developed for this purpose using a substitute polymer, FM-9 was made available for the actual blending attempt. GTA completed this phase of its contract in early January.

There were no indications that the GTA process had improved the blending rate of FM-9.

IMPORTANCE OF THE GTA PROCESS FOR COMMERCIALIZATION OF ANTIMISTING FUELS.

*(The views expressed herein are those of GTA and do not necessarily represent those of the FAA).

The purpose of GTA's contract with the FAA was to investigate the possibility of using the GTA process for point of fueling blending of antimisting fuels. The FAA was interested primarily in whether the GTA process would improve the blending of FM-9 in jet A. While there was no evidence developed under the contract which would indicate that the GTA process could be used to aid FM-9 blending, a more significant discovery was made.

GTA used its blending process and an off-the-shelf polymer to produce in a few minutes a fuel which exhibited antimisting characteristics equal to those of FM-9 and with only one-half the concentration. No additional additive or carrier fluid was required. This discovery indicates an alternative approach for antimisting fuel development based upon very high molecular weight, viscoelastic polymers.

The potential advantages of such an approach are significant both in cost savings and operation acceptance (figure 5-10).

First with regard to cost:
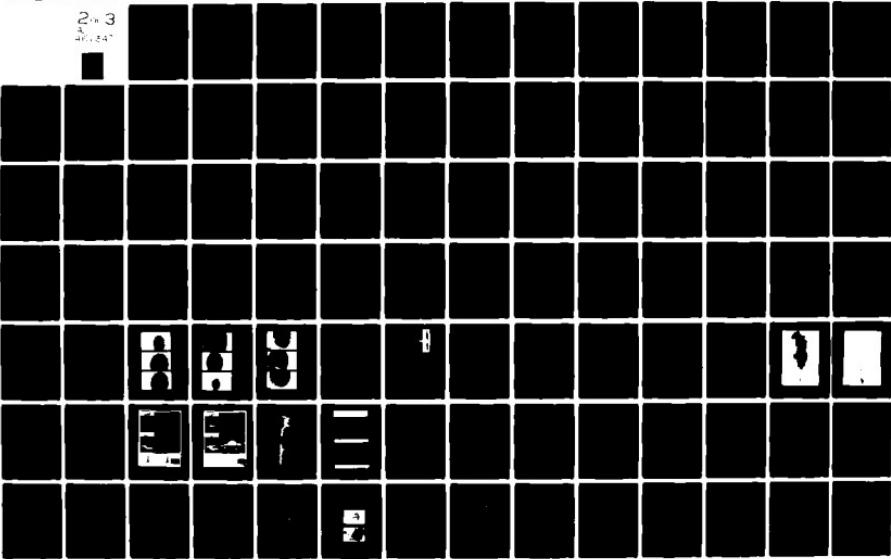
1. The cost of the antimisting additive material may be a major part of the cost of an antimisting fuel system. If a nonproprietary material, such as high molecular weight PIB can be used rather than a proprietary additive, it can be purchased in the open competitive market with consequent cost savings.

2. Simple polymers such as PIB are less expensive to produce.

3. There would be no additional additives required for promoting solution.

4. The GTA process works equally well with higher molecular weight polymers. Since increased molecular weight results in greater antimisting effectiveness there would be an opportunity to reduce concentrations of antimisting additives using higher molecular weight polymers.

5. Decreased concentrations of additive materials will mean less material to be transported, handled, stored, and blended.

6. A wide range of polymers could be examined, which might otherwise have been dismissed from consideration due to dissolving difficulties or degradation in storage and handling.

7. A bulk polymer like PIB can be transported, stored, and handled without special precautions, since it is stable under most atmospheric conditions.

8. Using the GTA process and an appropriate additive, there is no need for holding tanks for preblended fuels.

Second, use of the GTA process with a simple polymer could have a significant impact on operational acceptance of antimisting fuels (figure 5-11).

1. Blending directly into the aircraft fuel tank would eliminate degradation of fuels stored and distributed in solution.

2. A simple polymer system creates less quality control problems for the antimisting fuel system.

3. A pure hydrocarbon additive such as PIB is compatible with jet A fuel.

4. The antimisting additive would not have an affinity for water.

5. The antimisting fuel blends would be stable in solution in aircraft fuel tanks not subject to separation due to motion, temperature and pressure changes found in normal aircraft operations.

6. Rheological characterisitcs would be known and predictable.

7. Long chain polymers such as PIB could be degraded easily for return to neat fuel characteristics for burning in the engine.

8. Reduced concentrations of additive and use of a simple polymer would reduce anomolies in aircraft operating systems.

SUMMARY.

In summary, we believe that our contract with the FAA has produced results which
indicate a parallel path for antimisting fuel development, based upon high
molecular weight viscoelastic polymers, which can be blended directly into aircraft
fuel tanks using the GTA process.

CRITICAL ISSUE FOR COMMERCIALIZATION OF
ANTIMISTING FUEL - FUELING POINT BLENDING.

GTA HAS A PROPRIETARY PROCESS FOR RAPIDLY
DISSOLVING HIGH MOLECULAR WEIGHT POLYMERS.

FAA CONTRACTED WITH GTA TO APPLY GTA
PROCESS TO TWO ADDITIVES WITH ANTIMISTING
ADDITIVE.

FIGURE 5-1.   BLENDING ANTIMISTING FUEL
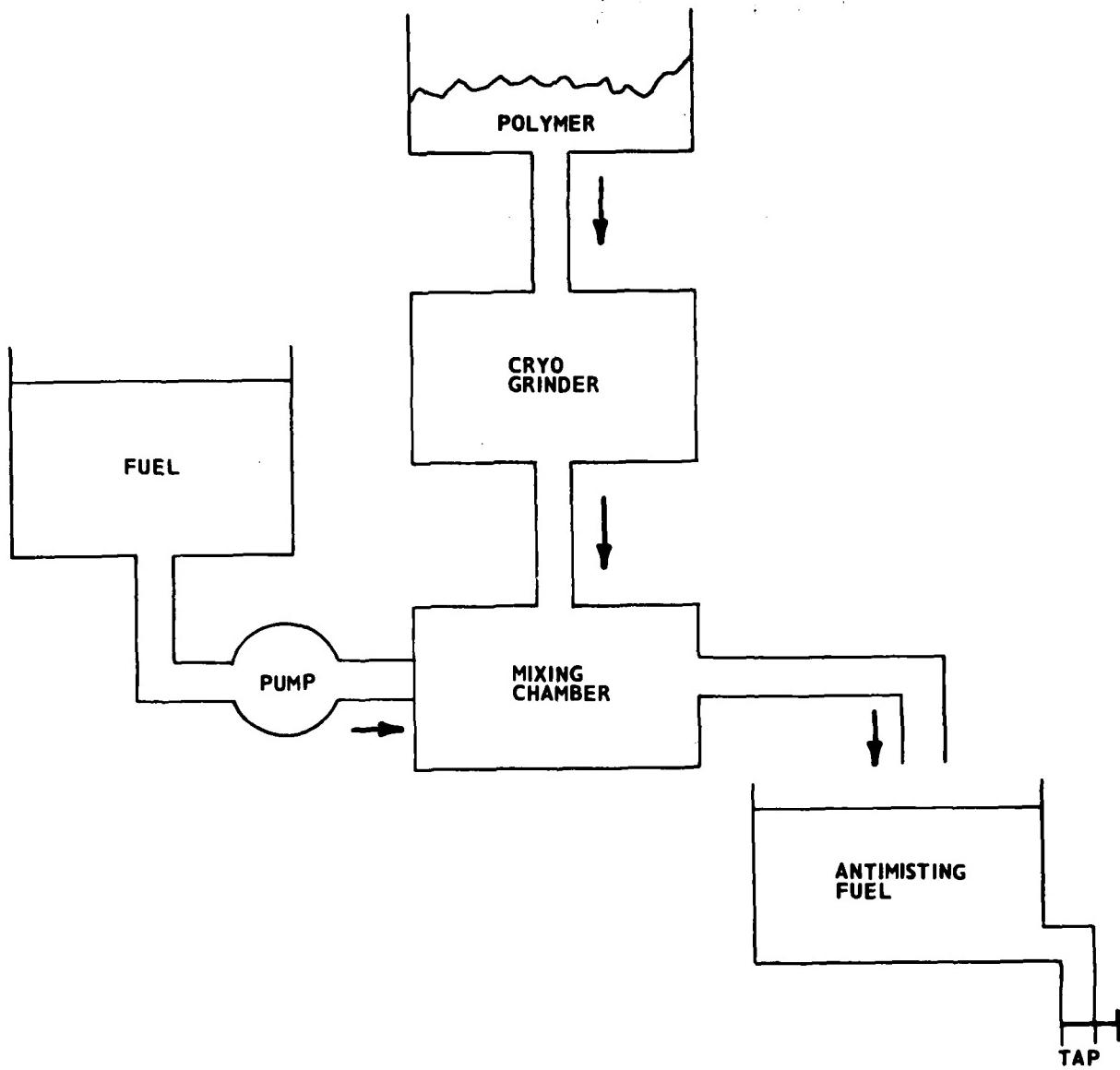
FIGURE 5-2.   GTA BLENDING SYSTEM

GTA BLENDING PROCESS APPLIED IN THE DRAG REDUCTION FIELD.

CORRELATION OF DRAG REDUCTION THEORY TO ANTIMISTING THEORY.

FAA'S REQUIREMENT FOR FUELING POINT BLENDING.

GTA/FAA CONTRACT TO BLEND ANTIMISTING ADDITIVES WITH JET A.

FIGURE 5-3.   BACKGROUND OF GTA/FAA CONTRACT

BLEND SMALL AMOUNTS OF ANTIMISTING FUELS USING
TWO DIFFERENT TYPE ADDITIVES

FAA TEST BLENDED FUEL SAMPLES

IF SAMPLES INDICATE ANTIMISTING BEHAVIOR PRODUCE
LARGE QUANTITIES FOR FAA WING SPILLAGE TEST

FIGURE 5-4.   GTA/FAA CONTRACT

FM-9

ICI PROPRIETARY ADDITIVE

ANTIMISTING BEHAVIOR RELATED TO FLOW INDUCED GELLATION

OPPANOL B-230

A NON-PROPRIETARY POLYMER MANUFACTURED BY BASF

ANTIMISTING BEHAVIOR RELATED TO VISCOELASTICITY

FIGURE 5-5.   TWO ANTIMISTING ADDITIVES SELECTED BY FAA FOR GTA BLENDING

BROOKFIELD VISCOMETER   VISCOSITY/CONCENTRATION

IMPULSE SPRAYER   MISTING BEHAVIOR

RHEOLOGY PUMP TEST   RHEOLOGICAL TEST RELATING
   TO ANTIMISTING BEHAVIOR

FIGURE 5-6.   ANALYTICAL TESTS
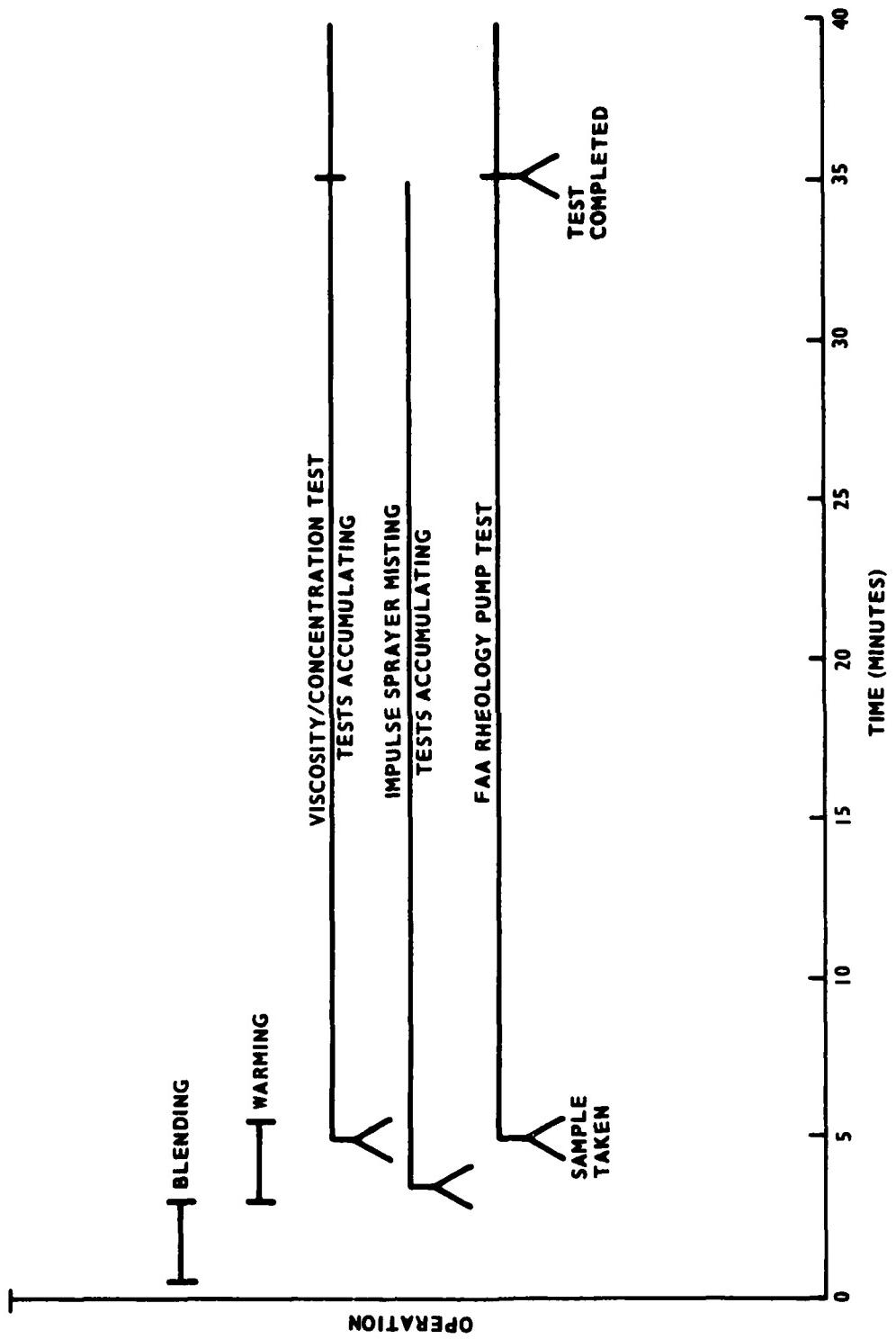
FIGURE 5-7. BLENDING AND TESTING 10 GALLONS OF 0.3 PERCENT PIB/JET A

5-10

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AMOUNT              7 GALLONS
BLENDING TIME       2 MINUTES
CONCENTRATION       .28%
TEST RESULTS
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VISCOMETER

--2 MINUTES AFTER BLENDING COMPLETED - .28% CONCENTRATION

--4 HOURS AFTER BLENDING COMPLETED .28% CONCENTRATION

IMPULSE SPRAYER

--3 MINUTES AFTER BLENDING COMPLETED-
  LONG THIN STREAM

RHEOLOGY PUMP

--SAMPLE TAKEN 2 MINUTES AFTER BLENDING GAVE INDICATIONS
  OF SIGNIFICANT ANTIMISTING BEHAVIOR

FIGURE 5-8.   FAA OBSERVED B-230 BLENDING RESULTS

OPPANOL B-230 AT .15% CONCENTRATION EQUAL IN PERFORMANCE

TO FM-9 AT .3% CONCENTRATION.

FIGURE 5-9.   FAA'S SUBSCALE FLAMMABILITY TESTS

POSSIBILITY OF USING A NON-PROPRIETARY POLYMER

SIMPLE POLYMER LESS EXPENSIVE TO PRODUCE

NO ADDITIONAL ADDITIVE TO PROMOTE SOLUTION

POSSIBLE REDUCTION IN CONCENTRATION BY INCREASING
MOLECULAR WEIGHT OF THE ADDITIVE

REDUCED COST OF TRANSPORTATION, STORAGE, HANDLING, AND
BLENDING.

POLYMERS CAN BE CONSIDERED WHICH MIGHT HAVE BEEN
DISMISSED AS A RESULT OF DISSOLVING DIFFICULTIES.

NO HOLDING TANKS FOR PRE-BLENDED SOLUTIONS

FIGURE 5-10.   POTENTIAL ADVANTAGES OF AN ANTIMISTING FUEL BASED UPON A HIGH MOLECULAR
VISCOELASTIC POLYMER AND THE GTA BLENDING PROCESS (COST SAVINGS)

ELIMINATION OF DEGRADATION OF FUELS IN STORAGE
AND DISTRIBUTION

SIMPLE POLYMER MEANS LESS QUALITY CONTROL PROBLEMS.

ADDITIVE COMPATIBLE WITH JET A.

NO AFFINITY FOR WATER.

STABLE IN SOLUTION IN AIRCRAFT FUEL TANKS.

KNOWN AND PREDICTABLE RHEOLOGICAL CHARACTERISTICS.

ADDITIVE EASILY DEGRADED FOR BURNING IN COMBUSTION CHAMBER.

LESS ADDITIVE AND USE OF SIMPLE POLYMER REDUCES
ANOMOLIES IN AIRCRAFT OPERATING SYSTEMS.

FIGURE 5-11.   POTENTIAL ADVANTAGES OF AN ANTIMISTING FUEL BASED UPON A HIGH
MOLECULAR VISCOELASTIC POLYMER AND THE GTA BLENDING PROCESS
(OPERATIONAL ACCEPTANCE)

Questions and answers following "Cryogenic Blending Polymer Additives in Fuel"

Discussions:

Mr. Fiorentino: Tony Fiorentino, Pratt & Whitney Aircraft. I have two questions. You said PIB was easier to degrade. Were you degrading it and what was your measure of degradation? The second thing was you thought it would be acceptable to the engine combustion chamber. How do you know that?

Mr. Trippe: We have run degradation tests in our laboratory. Polyisobutylene does degrade readily. Again, too readily for most of the pipeline applications. Regarding the second question, I'm suggesting the ease of degrading eliminates the problems that I understand exist for the burning of fuel in the combustion chamber. It seems that PIB could be returned to something very close to neat jet A fuel for that purpose.

Mr. Fiorentino: Are you using a viscometer to measure degradation?

Albert Haderman, GTA, Incorporated: We really haven't made degradation a primary part of this program. PIB is extremely sensitive to the degradation and the breakage of molecules. It is a problem in pipeline use that may be turned around to be looked at favorably in the antimisting fuel issue.

Mr. Paul Waters, GTA, Incorporated: We did measure the viscosity.

Mr. Fiorentino: The reason I raise that question is that simple viscosity is a test in which the measurements are not sensitive enough to the level of degradation that really is needed by some of the components.

Mr. Trippe: Is it possible that that's relative to the FM-9 and not to PIB?

Mr. Schmidt: If it degrades as easily as you say, how about tank sloshing?

Mr. Trippe: We have delivered material back and forth across the country with drag reduction tests and we have not had measurable degradation in that period. We haven't run any tests in our laboratories on tank slosh.

Mr. Schmidt: I would suggest along with Tony's comments, normal viscosity measurements are very misleading when you are dealing with the effect of viscosity due to a very high molecular weight constituent.

Dr. Wilford, Royal Aircraft Establishment: Did you try pumping this fluid at a low temperature of about -40° C?

Mr. Trippe: No, that was not a part of our tests low temperature pumping perform- ance may be influenced greatly by the concentration of antimisting additive. We see a possible redution in concentration which may help solve low temperature pumping problems.

Mr. Wilford: We have done pumping tests at low temperatures, down to about 0.2 percent of the PIB and all of these do have a problem after very low temperatures.

Mr. Waters: I would like to point out, there are two simple emperical equations that describe the behavior of dilute polymer solutions that everyone relies upon more or less. One is the Huggins equation and the other is the Marcleeg equation. They're appropriate for low polymer concentrations. Substituting the Marcleeg

equation into the Huggins equation shows that the concentration is much more important since the concentration is squared in the second term and cubed in the third term and so forth. For example, at 0.2 per cent (2,000 parts per million) a polymer such as PIB dissolved in benzene of a molecular weight of one million, will have a relative viscosity of 1.179. Whereas, you may reduce the concentration, by one order of magnitude, so that the concentration now becomes 200 parts per million, a very tolerable concentration and if you increase the molecular weight by two orders of magnitude, it turns out that the relative viscosity is lower than 0.179. In fact, it's 1.167. Since one anticipates that antimisting property should be a linear function of the molecular weight, our approach is that just any polymer which has acceptable viscoelastic properties might be investigated if one goes to very high molecular weights using very low concentrations.

ECONOMIC ASPECTS OF CONVERSION TO ANTIMISTING FUELS

By

S. SOKOLSKY

THE AEROSPACE CORPORATION

The Aerospace Corporation is conducting a study (figure 6-1) under contract with the FAA to assess the costs and benefits of converting the world turbine-powered jet aircraft fleet from jet A to AMK. Aerospace will evaluate the relationship between costs and benefits recognizing that, at this relatively early stage in the AMK project, considerable uncertainty exists in data and concepts for developing a suitable fuel. Thus, Aerospace expects to establish reasonable cost and benefit ranges and to analyze the best and worst cases as well as a nominal case. The methodology being developed will also permit a projection of the conditions for which the level of costs may be considered acceptable, relative to the benefits achieved.

In the initial phase (figure 6-2) of the economic analysis, which began in October 1980, Aerospace is gathering data on all aspects of AMK activity. This is being done through face-to-face and telephonic contracts with all individuals directly involved in the program, others who might be able to make a useful contribution, and still others who have indicated an interest in AMK. On the basis of the data gathered as well as a growing understanding of the various forces impinging on AMK development and use, Aerospace will suggest a working scenario depicting the changeover from jet-A to AMK. This scenario will be reduced to its component costs and benefits, each of which will be modeled with the aid of a relatively simple computer/pogram. It will then be possible to analyze the working scenario to determine cost and benefit relationships while accounting for data and scenario uncertainties. In later phases of the study, Aerospace hopes to update the models for each cost and benefit component; produce a far more detailed changeover scenario including schedules, descriptions, and costs of each event; derive an improved cost/benefit methodology; and update the analysis. As part of this activity, it is proposed to perform a series of tradeoff studies in order to evaluate alternative fuel modification methods; assess other technology options also leading to decreased fire danger and determine the impact of uncertainties in costs, operational factors and benefits.

For the present analysis, it will be assumed that the world consists only of turbine-powered airline aircraft categorized as widebodies, narrow bodies, and large turboprops (figure 6-3). Consistent with the status of fuel modifier technology, a proprietray product of ICI, known as FM-9 will be taken as the candidate additive. At the present level of FM-9 technology development, the polymer must be mixed with selected carrier fluids to form a slurry prior to blending with jet-A. Thus, it will be assumed that this slurry is delivered to airports independent of jet-A delivery. In-line blending at the point of aircraft fueling will also be assumed. This will affect different airports different ways, depending upon the type of fueling system used. For airports using tanker-pumper trucks, it is not clear that reasonable modification of these extremely large vehicles is possible and they may, therefore have to be replaced. Finally, it is assumed that significant modifications to aircraft fuel systems and powerplants will be needed. For example, non-shear pumps to eliminate AMK degradation will have to be installed.

In those aircraft with a circulating fuel system, a major redesign could be required. Degraders will be a necessity to prepare the fuel for proper use by the turbine engines, in which such hardware as spray nozzles may have to be replaced.

The scenario described above permits the identification of significant cost areas (figure 6-4. Implementation costs will include retrofitting the existing turbine aircraft fleet; making new aircraft production line changes; and modifying the airport infrastructure as required. Current information indicates that operating and maintenance costs will include:

1. Production of the fuel modifier and distribution of the fuel modifier on the airport.

2. Additional fueling costs if a longer time and more manpower are required.

3. Added costs if fuel equilibration requires ground delays for the aircraft.

4. Additional energy costs if fuel temperatures must be regulated.

5. The cost of additional fuel to make a given trip, due to the lower engery content of AMK (approximately 0.4 percent lower heating value than jet-A) and to the need to operate degraders.

6. Possibly higher maintenance costs for inspection and cleaning to free the fuel system of gelled particles.

In carrying out the initial cost analysis; a number of pivotal assumptions are being made (figure 6-5). It will be assumed that aircraft retrofit may be accomplished during a scheduled maintenance period. It is assumed that fleet size, number of gate positions required, and maintenance facility needs are not impacted by conversion to AMK. This requires that fueling with AMK be accomplished at current rates; that fuel additive relaxation occurs quickly; that maintenance intervals will not have to be significantly decreased; and that maintenance downtime will not be significantly increased. Off-loading of fuel will also be assumed as not required on a regular basis. Finally, air turbulence or sudden maneuvers will not cause the fuel to gel. In later phases, these pivotal assumptions will be examined and may be relaxed. For example, a complete teardown and rebuilding of a fuel system may be required. Thus retrofit may not be possible during the scheduled maintenance period. This would cause substantial added ground time.

In the initial study phase, the following benefit areas are being considered (figure 6-6).

   1. Reduction in injuries and fatalities.
   2. Reduction in damaged aircraft.
   3. Reduction in cargo losses.

In later phases, other benefits, such as increases in passenger demand due to perceived safety improvements, will be considered. A number of factors affect the level of benefits (figure 6-7). For example, assumptions are being made of world fleet composition in later years. A recent study forecasted a 24-percent increase in the size of the jet fleet in 1994 relative to that in 1979 (excluding the Eastern Bloc and China), with 43 percent of the fleet being wide-bodied aircraft. Upwards of 500 large turbo props are also expected in the fleet at that time.

Furthermore, rapid growth of jet fleets in third world countries could produce higher casualty rates in that sector as it did in the rest of the free world in the 1970's. Airport operations are expected to increase by 38 percent in this time period with essentially no change in the number of airports. Since most accidents of interest in this study occur during approach and landing or takeoff, this situation could serve to impair safety. Progress is also being made in other technology areas, and options other than AMK are under development which could also result in less fire danager. It should be noted that the benefits of installing several technologies are not generally additive and that the technology choices may also be interdependent.

Before discussing the cost benefit methodology to be applied in this study, it is instructive to examine the existing aircraft accident data base (figure 6-8). In the area of fire injuries and fatalities, Aerospace is performing an independent analysis and has found that the data base is somewhat meager in many instances. The causes of injuries and death are often uncertain, due to the sketchy nature of the accident reports. Some accidents are reported only by one or two sentence summaries (Aeroflot accidents are in this category); other accidents are well reported and the results clearly stated. With respect to fires potentially preventable by using AMK, 113 events between 1960 and 1980 bear detailed analysis. Since all of the characteristics of AMK fuels are not yet known, it cannot be stated with certainty that these accidents would not have resulted in fire, or is it entirely clear that fatalities could have been prevented even if fire had not occurred. In the methodology adopted for the present study, both fatalities and serious injuries were examined. Fatalities were categorized into confirmed and estimated fire deaths. The data were developed in terms of 4-year moving averages (figure 6-9). The analysis indicated annual averages of 42 confirmed and 31 estimated deaths, for a total of 73. A major peak occurs in the confirmed fatalities curve due to the Tenerife and Pago Pago accidents. On the other hand, the data base used does not include the year 1980, which accounted for a very low number of fatalities.

The historical accident data were also examined to estimate the salvageability of damaged but unburned aircraft (figure 6-10). Accidents were categorized as follows: aircraft broken-up and burned-out; aircraft landing gear collapsed, aircraft slid, and fire occurred; aircraft landing gear collapsed, aircraft slid, engine(s) tore loose, and fire occurred; only minor aircraft damage was probable if fire had not been present; aircraft damage could not be determined because details were sketchy; and aircraft damage was judged to be equivalent with or without AMK (these accidents were excluded). The estimated number of salvageable aircraft could then be corrected for fleet composition and this quantity, in turn, corrected for forecasted fleet size and numbers of operations. The salvageability benefit could then be determined (figure 6-11). Again, the data were analyzed using 4-year moving averages for all jets as a group and all turboprops as a group. The resulting 20-year annual averages for the first category were 2.4 salvageable jets and 0.9 salvageable turboprops, for a total of 3.3 aircraft. A significant rising trend in the jet data between 1968 and 1974 is explainable by the very large drop in piston-powered aircraft in the fleet (28 percent in 1968 to 14 percent in 1974).

Cost/benefit analysis is a technique for evaluating the benefits to society or industry of specific allocations of resources (figure 6-12). There are a number of approaches which may be taken in performing cost/benefit analyses, depending upon the population being studied. Costs and benefits will vary depending upon whether the study population is the world, the nation, or the airline industry. In the

case of the world and the nation, costs may be defined as the value of resources which are unavailable to alternative economic activities because resources are allocated to AMK, in this case. Since the economy is constrained by finite resource availability, certain other goods and services cannot be produced. Benefits may be defined as the value of resources which become available for alternative economic activities as the result of the AMK activity. Resources are saved and may be used to produce additional goods and services. For the airline industry, costs are the net additional incurred because of AMK use. The additional gross costs are reduced through tax deductions. Benefits may be defined as cost reductions associated with accidents in which there are fewer fatalities and less damage. In addition, revenue increases may occur because of the public's perception of the improved safety of airlines.

Actual cost/benefit calculations are carried out on a present value basis (figure 6-13). Streams of annual benefits and costs, considered over the lifetime of the investment, are each reduced to a single value at a selected point in time, typically taken as the present. The computation is made using a discount rate as a weighing factor. The discount rate has the effect of reducing the value of future costs and benefits. This is done in recognition of the fact that individuals normally prefer to receive and spend income early (now rather than later); that most individuals believe that investments are risky and are, therefore, adverse to risk-taking; and finally, that the dollar is likely to have a lower value in the future in an inflationary economy.

With these concepts, it is useful to define the following figures of merit:

1. The net present value, or the difference between the present value of benefits and the present value of costs.

2. The benefits per dollar of cost, or the present value of benefits divided by the present value of costs.

3. The cost per passenger saved, or the present value of costs divided by the number of fatalities reduced.

4. The value of reducing fatalities, or the condition under which the present value of benefits and the present value of costs are equal.

Only worldwide benefits and costs are being considered in the initial phase of this study (figure 6-14). All figures of merit will be computed, but the last figure of merit, i.e., the value of reducing fatalities, should be of particular interest because it will indicate the conditions under which the level of costs may be considered acceptable relative to the benefits achieved.

6-4

- ASSESS COSTS OF CONVERTING WORLD TURBINE-POWERED CIVIL AIRCRAFT FLEET FROM JET-A TO AMK

- IDENTIFY AND ESTIMATE VALUE OF DIRECT AND INDIRECT BENEFITS FROM ADOPTION OF AMK FUEL WORLDWIDE

- EVALUATE RELATIONSHIP BETWEEN COSTS AND BENEFITS, RECOGNIZING UNCERTAINTIES IN DATA AND CONCEPTS

- PROJECT CONDITIONS FOR WHICH LEVEL OF COSTS MAY BE CONSIDERED ACCEPTABLE RELATIVE TO BENEFITS ACHIEVED

FIGURE 6-1. STUDY PURPOSE

● INITIAL PHASE

   ● GATHER DATA ON ALL ASPECTS OF AMK ACTIVITY
   ● DEVELOP WORKING SCENARIO OF CHANGEOVER FROM JET-A TO AMK
   ● IDENTIFY COST AND BENEFIT COMPONENTS AND CONSTRUCT
     SIMPLIFIED MODELS OF EACH
   ● CONSTRUCT COST/BENEFIT COMPUTER MODEL
   ● ANALYZE WORKING SCENARIO, ACCOUNTING FOR DATA AND
     SCENARIO UNCERTAINTIES

● LATER PHASES

   ● CONTINUE DATA GATHERING AND UPDATE MODELS OF EACH COST
     AND BENEFIT COMPONENT
   ● PRODUCE DETAILED CHANGEOVER SCENARIO
     ● INCLUDE SCHEDULES, DESCRIPTIONS, COSTS
   ● IMPROVE COST/BENEFIT METHODOLOGY AND ANALYSIS
   ● PERFORM TRADE STUDIES
     ● EVALUATE ALTERNATIVE FUEL MODIFICATION METHODS
     ● ASSESS OTHER OPTIONS (technologies) LEADING TO LESSENED
      FIRE DANGER
     ● DETERMINE IMPACT OF VARIOUS UNCERTAINTIES IN COSTS,
      OPERATIONAL FACTORS AND BENEFITS

FIGURE 6-2.   STUDY APPROACH

- WORLD CONSISTS OF TURBINE POWERED AIRLINE AIRCRAFT

  - WIDEBODIES
  - NARROW BODIES
  - LARGE TURBOPROPS

- FUEL MODIFIER IS FM-9 POLYMER

  - DELIVERY TO AIRPORTS OCCURS AS MIXTURE OF POLYMER AND CARRIER FLUIDS (slurry)

- BLENDING OCCURS AT POINT OF AIRCRAFT FUELING

  - FOR HYDRANT SYSTEMS
    - AIRPORT INFRASTRUCTURE REMAINS RELATIVELY UNCHANGED
    - MAJOR CHANGES TO HYDRANT TRUCKS
  - TANKER-PUMPER SYSTEMS
    - TRUCKS MAY HAVE TO BE REPLACED

- AIRCRAFT FUEL SYSTEMS AND POWERPLANTS REQUIRE MODIFICATION

  - NON-SHEARING PUMPS MUST BE USED
  - FUEL CIRCULATION SHOULD BE LIMITED
  - DEGRADER MUST BE ADDED
    - MAY BE ON EACH ENGINE
  - SPRAY NOZZLES MUST BE CHANGED ON EACH ENGINE
    - OTHER ENGINE CHANGES MAY BE REQUIRED

FIGURE 6-3.   CONVERSION SCENARIO DESCRIPTION

- IMPLEMENTATION COSTS (annualized)

    - RETROFIT OF EXISTING FLEET

    - ADDITIONAL NEW AIRCRAFT COSTS (zero assumed)

    - RETROFIT OF AIRPORT INFRASTRUCTURE

- OPERATING AND MAINTENANCE COSTS (annualized)

    - PRODUCTION OF FUEL MODIFIER

    - DISTRIBUTION OF FUEL MODIFIER TO AIRPORTS (zero assumed)

    - STORAGE AND DISTRIBUTION OF FUEL MODIFIER ON AIRPORT (zero assumed)

    - ADDITIONAL FUELING COSTS (time, manpower, delay, energy)

    - ADDITIONAL COST DUE TO GREATER FUEL USE

    - ADDITIONAL MAINTENANCE COSTS

FIGURE 6-4.   COST AREAS

- AIRCRAFT RETROFIT ACCOMPLISHED DURING SCHEDULED MAINTENANCE

- FLEET SIZE, NUMBER OF GATE POSITIONS, MAINTENANCE FACILITIES NOT IMPACTED

- FUELING WITH AMK ACCOMPLISHED AT CURRENT RATES

- RELAXATION TIME AFTER FUELING LESS THAN 15 MINUTES

  - GATE HOLDS NOT REQUIRED

  - SMALL STATION OPERATIONS NOT SIGNIFICANTLY IMPAIRED

- MAINTENANCE INTERVAL AND PROCEDURES NOT SIGNIFICANTLY AFFECTED

- MAINTENANCE DOWNTIME NOT SIGNIFICANTLY INCREASED

- OFF-LOADING OF FUEL NOT REQUIRED ON A REGULAR BASIS

- AIR TURBULENCE DOES NOT DEGRADE FUEL

FIGURE 6-5.   PIVOTAL ASSUMPTIONS WHICH COULD BE RELAXED IN FUTURE TRADEOFF STUDIES

- INITIAL STUDY PHASE VALUES
    - ANNUALIZED REDUCTIONS
        - FATALITIES
        - INJURIES
        - DAMAGED AIRCRAFT
        - LOST CARGO

- LATER STUDY PHASE VALUES (annualized)
    - AIR PASSENGER DEMAND INCREASE DUE TO SAFETY IMPROVEMENTS
    - ENVIRONMENTAL EFFECTS OF AMK IMPLEMENTATION (may be negative benefit)
    - REDUCTION IN GRIEF FROM REDUCED INJURIES AND FATALITIES
    - REDUCTION IN FIRE FIGHTING EQUIPMENT AND PERSONNEL

FIGURE 6-6.   BENEFIT AREAS

- WORLD FLEET COMPOSITION (excluding Aeroflot and CAAC)

  - JET FLEET IN 1994: 7300 AIRCRAFT (24% increase over 1979)
  - 43% WIDEBODIES
  - APPROXIMATELY 500 LARGE TURBOPROPS
  - GROWTH IN THIRD WORLD JET FLEET
    - MAY IMPLY HIGHER CASUALTY RATE IN THAT SECTOR

- OPERATIONS AT AIRPORTS

  - INCREASE OF 38% BY 1994 RELATIVE TO 1979

- OTHER CONTINUING TECHNOLOGICAL IMPROVEMENTS (could be considered in future tradeoff studies)

  - CASHWORTHINESS OF FUEL SYSTEM COMPONENTS
  - NEW INTERIOR MATERIALS
  - NEW LANDING AIDS
  - AIR TRAFFIC CONTROL PROCEDURES
  - WEATHER TRACKING AND FORECASTING

- CUMULATIVE IMPACTS OF OTHER TECHNOLOGICAL IMPROVEMENTS

  - BENEFITS NOT GENERALLY ADDITIVE
  - TECHNOLOGY CHOICES INTERDEPENDENT

FIGURE 6-7.   FACTORS AFFECTING AMK BENEFITS

- CAUSE OF INJURY/DEATH OFTEN UNCERTAIN

  - SKETCHY DETAILS PROVIDED ON MANY ACCIDENTS
    - LEAVE MANY QUESTIONS UNANSWERED
  - SOME ACCIDENTS REPORTED BY ONE OR TWO SENTENCE SUMMARIES
    - AEROFLOT IS AN EXAMPLE
  - GOOD ESTIMATES AVAILABLE FOR SOME

- INJURIES/DEATHS POSSIBLY PREVENTABLE BY AMK

  - DATA BASE INCLUDES 113 ACCIDENTS FROM 1960 THROUGH 1980
  - INVESTIGATIONS CONTINUING ON FIRE SPREAD RATE IF AMK HAD BEEN PRESENT
  - TIMING OF FIRE SPREAD IN HISTORICAL ACCIDENTS OFTEN UNCERTAIN
    - ONE AIRCRAFT WITH MINIMAL SURVIVORS IGNITED 15 MINUTES AFTER CRASH
  - WEATHER CONDITIONS (wind speed/direction) AT TIME OF CRASH OFTEN UNAVAILABLE
  - IMPACT SPEED NOT ALWAYS INDICATED
    - RANGE OF AMK EFFECTIVENESS STILL UNDER INVESTIGATION

- METHODOLOGY

  - FATALITIES STUDIED

  - DATA DIVIDED INTO CONFIRMED AND ESTIMATED FIRE DEATHS
    - SOME DEATHS MAY NOT BE PREVENTABLE
    - FOR ACCIDENTS WITH INCOMPLETE DATA, FIRE DEATHS ESTIMATED FROM FATALITIES

FIGURE 6-8. FIRE INJURY/DEATH DATA

- CURVES INDICATE FOUR YEAR MOVING AVERAGES

- TOTAL DEATHS = CONFIRMED + ESTIMATED

- PEAK IN CONFIRMED DEATHS DUE LARGELY TO TENERIFE AND PAGO PAGO ACCIDENTS

- 1980 DATA NOT INCLUDED (apparently low value)

- TWENTY YEAR AVERAGES

  - CONFIRMED = 42
 - ESTIMATED = 31
  - TOTAL   = 73
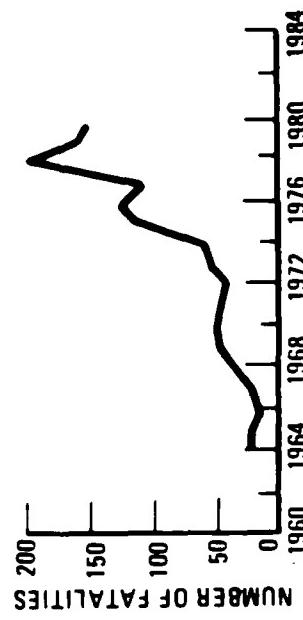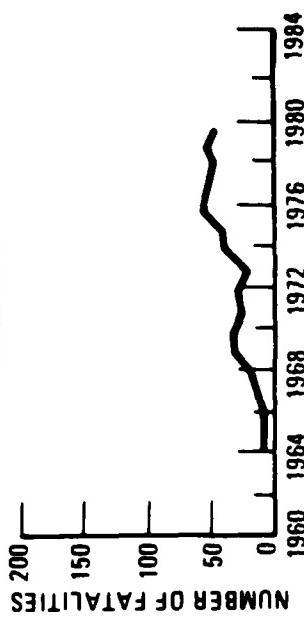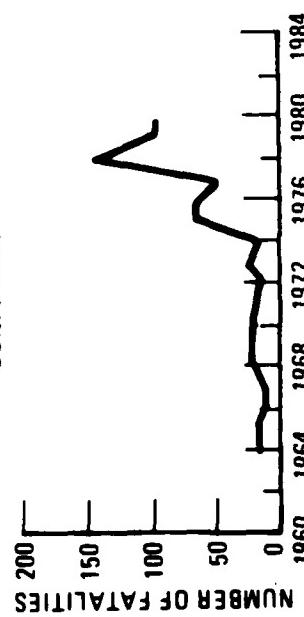
FIGURE 6-9.   FIRE DEATHS — 4-YEAR MOVING AVERAGES

- METHODOLOGY
  - CATEGORIZE HISTORICAL ACCIDENTS
    - DATA BASE INCLUDES 113 ACCIDENTS FROM 1960 THROUGH 1980
    - ESTIMATE SALVAGEABILITY
  - ADJUST SALVAGEABILITY ESTIMATE FOR FLEET COMPOSITION
  - FORECAST FLEET SIZE AND OPERATIONS
  - ESTIMATE BENEFIT

- ACCIDENT CATEGORIES
  - AIRCRAFT BROKEN UP, THEN BURNED
    - LARGEST CATEGORY IN GROUP
    - SALVAGEABLE IN NO FIRE OR EXTINGUISHABLE FIRE CASES
    - HIGH PROPORTION OF TURPOPROPS
    - HIGH PROPORTION OF TRAINING ACCIDENTS
  - LANDING GEAR COLLAPSED, LONG SLIDE, FIRE
    - REQUIRE DAMAGE ESTIMATE DUE TO SLIDE
    - LESS FREQUENT IN RECENT YEARS
  - LANDING GEAR COLLAPSED, LONG SLIDE, ENGINE(s) TORN OFF, FIRE
  - ONLY MINOR DAMAGE PROBABLE IF FIRE NOT PRESENT
  - UNDETERMINED DAMAGE (details unavailable)

- EXCLUDED ACCIDENTS
  - DAMAGE WITH AMK USE ESTIMATED AS EQUAL TO DAMAGE WITHOUT AMK USE

FIGURE 6-10.   VALUE OF DAMAGED (BUT UNBURNED) AIRCRAFT

FIGURE 6-11. DAMAGED BUT SALVAGEABLE AIRCRAFT BROKEN UP, BURNED OUT CATEGORY

- A TECHNIQUE FOR EVALUATING THE BENEFITS TO SOCIETY OR INDUSTRY OF SPECIFIC ALLOCATIONS OF RESOURCES

- COSTS AND BENEFITS VARY WITH STUDY POPULATION
  - WORLD
  - NATION
  - AIRLINE INDUSTRY

- WORLD AND NATION
  - COSTS
    - VALUE UNAVAILABLE TO ALTERNATIVE ECONOMIC ACTIVITIES WHEN RESOURCES ARE ALLOCATED (in this case to AMK)
    - LOSS IN PRODUCTION OF OTHER GOODS AND SERVICES BECAUSE ECONOMY CONSTRAINED BY FINITE RESOURCE AVAILABILITY
  - BENEFITS
    - VALUE OF RESOURCES WHICH BECOME AVAILABLE FOR ALTERNATIVE ECONOMIC ACTIVITIES
    - RESOURCES SAVED AND ADDITIONAL GOODS AND SERVICES PRODUCED

- AIRLINE INDUSTRY
  - COSTS
    - NET ADDITIONAL COSTS INCURRED FOR AMK USE
    - ADDITIONAL GROSS COSTS REDUCED BY TAX DEDUCTIONS
  - BENEFITS
    - COST REDUCTIONS ASSOCIATED WITH ACCIDENTS
    - REVENUE INCREASED DUE TO IMPROVED SAFETY

FIGURE 6-12.   COST/BENEFIT ANALYSES

o STREAMS OF ANNUAL BENEFITS AND COSTS EACH REDUCED TO
   SINGLE VALUE AT SELECTED POINT IN TIME

o DISCOUNT RATE USED AS WEIGHTING FACTING TO REDUCE VALUE
   OF FUTURE COSTS AND BENEFITS

   o INDIVIDUALS PREFER TO RECEIVE AND SPEND INCOME EARLY

   o MOST INDIVIDUALS ADVERSE TO RISK TAKING (INVESTMENTS ARE RISKY)

   o DOLLARS HAVE LOWER FUTURE VALUE IN INFLATIONARY ECONOMIC
      ENVIRONMENT.

FIGURE 6-13.   PRESENT VALUE OF BENEFITS AND COSTS

6-17

- ONLY WORLDWIDE BENEFITS AND COSTS CONSIDERED IN INITIAL PHASE

- FIGURES OF MERIT

  - NET PRESENT VALUE, i.e., PRESENT VALUE OF BENEFITS LESS PRESENT VALUE OF COSTS

  - BENEFITS PER DOLLAR COST, i.e., PRESENT VALUE OF BENEFITS DIVIDED BY PRESENT VALUE OF COSTS

  - COST PER PASSENGER SAVED, i.e., PRESENT VALUE OF COSTS DIVIDED BY PASSENGERS SAVED

  - VALUE OF REDUCING FATALITIES, i.e., CONDITION FOR PRESENT VALUE OF BENEFITS TO EQUAL PRESENT VALUE OF COSTS

FIGURE 6-14.   EVALUATION OF BENEFITS AND COSTS

6-18

Questions and answers following "Economic Aspects of Conversion to Antimisting Fuels"

Discussions:

Mr. E. Thomas: Ed Thomas, Air Transport Association.   I really don't have a question at this point, but I do have an observation. You're using an accident data base which goes back to the 1960's. This picks up a number of accidents to turbine powered aircraft for which corrective action has been taken through regulatory changes by the FAA. Those accidents would no longer occur. If you look at the accident rate, the fatality rate over 20 years, there is a steady downward trend. I think you're biasing the information, particularly when you get into the cost benefit area by using what I call ancient accident data. The SAFER Committee tried a similar kind of analysis. The committe found the same thing that you have, that it was very difficult to find adequate accident data. I would suggest that you read the SAFER Committee report in that particular area.

Mr. I. Thomas: Ivor Thomas, Boeing Company. A comment as far as the new airplanes are concerned, the new airplanes you're talking about don't exist. The 757, 767, the A310 are hard airplanes that exist right now, and to redesign them to treat any new fuel is going to be a substantial cost. The existing airplanes that are coming out of the door also have that cost. I suspect all the new airplanes that are going to be delivered in the next 20 years, probably 80 percent of them, are already designed. I would caution you to put that kind of analysis in your model. I suspect the airlines would have a similar comment about maintenance.

Mr. Taylor: Cranfield Institute, England. Have you assumed that no accidents will be caused by the use of these additives?

Mr. Sokolsky.   I guess the answer to that is, we assumed there would be no fire fatalities as a result of the use of antimisting fuel.

Mr. Reiss: Peter Reiss, American Airlines. One of your presentations suggested there would be an increased demand by passengers as you increase the safety, because when there is an accident in which we lose passengers, the airlines have a reduction in passengers. I can't see how you can take that into consideration as one of your benefits.

Mr. Sokolsky: We did indicate that's a possible benefit that we want to look at in the future, but we're not looking at it right now. Clearly, it seems to us that with increased safety of aviation, the airline business, perhaps, would induce more people to fly than fly today.

Mr. Reiss: The second thing is we assume the aircraft comes in for maintenance 2 days once a year. I think we get into our fuel tanks about every third year, so, you can't say we can do this in one year. This is the kind of misconception that occasionally goes through these programs and is presented to the airline industry and we are accused of dragging our feet, this is not so. It is the people that come up with the results of a study that do not know anything about our business or the way we conduct our business.

Mrs. Wolff: We will definitely take that into consideration when we go into a detailed analysis.

Mr. E. Thomas: I would like to make another point. You are talking about maintenance, of doing these modifications during scheduled maintenance and that sort of thing, so I'm assuming you're considering only the modification costs themselves. From what I have gathered from the discussion here, we're going to be getting the airlines involved in the modifications in the hot section of the engine, which is the heart of the jet engine. We could suddenly be faced with building up the reliability of the hot section components back to where it is now. That occurred when we went to the so-called reduced smoke burner cans. I'm not sure we're back up where we were with the old burner, and that's been done for about 6 years now. So, another cost that you have to consider is what are the potential effects on engine maintenance and engine operations to reachieve the reliability that we're enjoying now?

Mr. Sokolsky: I think if you look at my slides, you will notice that we have made a very pivotal assumption. Namely, that there is a period of downtime and beyond, that maintenance is not going to be increased because of changes that have to be made to alter the airplane or its power plant. That's an assumption that's being made only for this very first study. I think the FAA said earlier that this is going to be a continuing activity. If you look at the 4 year plan that the FAA recently published, they have communicated that this activity is going to go on for the next 2 or 3 years. We plan on improving this analysis as time goes on. There's no question that we're going to try to understand what the effect on maintenance might be and we will certainly take that into account in our analysis.

Mr. E. Thomas: I don't want to leave the impression that the airlines are opposed to this program. In fact, we have been supporting this ever since we heard of it. We think it's the best thing for us if it works. What we want is a good analysis. We don't want to start with the answer and work with the problem backward. We want to find out what the answer is going to be through the problem from start to finish.

Mr. Wilford: I would like to support Ed Thomas in that the one thing that surprises me is that since this cost benefit program began, I'm not aware of your having approached any airline to ask them for their opinion on some of the subjects that you put in your presentation.

Mr. Sokolsky: We have not been on contract very long. Secondly, I have approached several airlines and have not gotten very much information from them. Most of the information I have gotten so far is from Lockheed, an aircraft manufacturer. They have by far been the most cooperative. Of course, they do a lot of work in maintenance. Their people have been very cooperative in giving me information. Now, as far as the airlines themselves are concerned, I am eventually going to approach everybody, every single one in the country to get their feeling about this work.

Mr. E. Thomas: We don't intend to do this job for him but we'll help in any way. We will provide information. We will be happy to try.

UK PROGRAMME ON SAFETY FUELS

By

S. P. WILFORD

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

The UK programme on safety fuels has, from its inception, been a collaborative effort between the RAE and the Paints Division of ICI. The main aim of this work has been to try and develop aircraft fuels which will be much less likely to catch fire during a potentially survivable crash. During such a crash, an aircraft is subjected to highly disruptive forces which can lead to fracture of fuel lines, rupture of fuel tanks, etc., and a primary cause of fire, particularly with aircraft fueled on low-volatility fuels such as aviation kerosene, is the formation of flammable mists. These arise because of the high speed of escaping fuel relative to the surrounding air. Mists are readily ignited and they can result in a crashing aircraft being engulfed in a short-lived fireball which can act as a bridge between any ignition source which may be present and any major fuel spillage. Reduction of mist formation should, therefore, significantly reduce the chance of a serious fire during a crash.

Two films illustrate important features of antimisting fuels. The first outlines the development of an aircraft safety fuel, the fuel concerned, being kerosene, containing a small amount of very high molecular weight polymeric additive. This film includes some tests of fire resistance. The second film briefly shows some engine ingestion tests done with the latest safety fuel — FM-9 modified kerosene.

FILMS.

The films clearly show the good fire suppression properties of AMK and support the view that such fuels can greatly reduce the risk of fire in a potentially survivable crash.

Turning to matters other than fire resistance, the first film also outlined problems likely to be associated with the use of antimisting fuels in aircraft; e.g., pumping problems, deposits in engines, difficulties with engine fuel control systems, water compatibility, etc. That film was, however, made some time ago, and since then marked progress has been made in dealing with many of these problems and the latest antimisting fuel, FM-9 modified kerosene, has greatly improved properties from a number of aspects. It is this fuel that has been the subject of a joint study by the United Kingdom and United States under a MOU signed in 1978.

The matter of fuel handling is one that the United Kingdom has long seen as vital because, no matter how good a safety fuel is from a fire resistance aspect, it is useless unless it can be put into the aircraft fuel tanks, transferred from these to the engine, and finally burned in a combustion chamber. We therefore see AMK being used, in practice, with the method outlined below.

1. Introduction of additive immediately prior to aircraft tanks.
2. Degradation of AMK upstream of engine. Degradation is the breaking up of large polymer molecules to smaller fragments.

Thus, when the MOU was agreed, the following basic questions were posed with regard to the feasibility of using AMK in aircraft.

1. Can the additive be made available in adequate quantities and at an acceptable cost with adequate control of quality for worldwide deployment?

2. What degree of protection would AMK provide in post crash fuel fires?

    a. A few minutes after refuelling; i.e., typically in the takeoff case.

    b. At the end of a typical flight cycle; typically in the approach/landing case.

3. What changes, if any, are necessary to enable a civil aircraft to use AMK? For example, are changes necessary to the fuel system tanks, pumps, filters, etc., and/or to the engine fuel management system?

4. Is it feasible in day-to-day commercial operation to blend the additive with kerosine at the fuelling point?

5. To what degree must AMK be degraded before it is suitable for operation in an engine system, and how can this controlled degradation be achieved?

The UK programme on FM-9 fuel has been directed towards trying to find answers to some of these questions.

ADDITIVE COST, AVAILABILITY AND QUALITY CONTROL.

The first two items, additive cost and availability, are primarily a matter for the supplier (ICI) to deal with. In general, there should be no difficulty in making the additive on the scale required for worldwide operation provided that there is the necessary commercial incentive. However, there are one or two points which are pertinent to future quality control. The fuel that is currently being used contains FM-9 additive and carrier fluid in aviation kerosene, the concentrations of the additive and carrier fluid being 0.3 and 0.6 percent, respectively. During the development phase, there have inevitably been some problems with FM-9 fuel; perhaps the most striking case being associated with impurities in a raw material supplied to ICI. Here, two important properties of the fuel were affected — the amount of energy required to degrade it, and the rate of dissolution of additive/ carrier fluid dispersions. The impurities were present at low concentrations but the problem was overcome. Use of FM-9 fuel would, therefore, require very strict monitoring of the additive, the carrier fluid components, and the fuel itself and much work is needed to develop the necessary quality control techniques.

FIRE RESISTANCE: WHAT DEGREE OF PROTECTION WOULD AMK PROVIDE IN POST CRASH FUEL FIRES?

In the United Kingdom, fire resistance has been determined mainly with the RAE rocket sled test. In the standard test, a tank containing 10 or 20 gallons of fuel is propelled on a sled into an arrester wire. The deceleration produced by the latter causes a slit to open in the leading edge of the tank and fuel is then flung forward onto an ignition source. In the course of these tests, a wide variety of ignition sources have been used — flames, hot ducts, arcs, running jet engines.

This test has been shown to subject spilled fuel to relative fuel/air velocities of up to 170 knots, and the very large number of tests that have been carried out have shown conclusively that FM-9 additive at concentration of 0.3 percent confers a high degree of fire resistance. Wing-spillage tests at the FAA Technical Center have confirmed these results.

The MOU poses the question of the degree of fire resistance at takeoff and at landing.

  a. Takeoff Conditions (Question B1)

The great majority of testing has been done on AMK which has been allowed several days to equilibrate having been prepared at an ICI plant (Wilmington Delaware, in the USA or Slough in England) and shipped to the test site. However, only data strictly relevant to takeoff conditions are that obtained with freshly blended fuel. Some tests at RAE, in which dispersion was blended with Jet A-1, showed that acceptable fire resistance is obtained with 10-15 minutes of blending provided that the base fuel temperature is above -5° C (23° F).

  b. Fire Resistance at Landing (Question B2)

As with the takeoff case, many of the fire resistance results are not strictly applicable to the landing situation, since fuel may have been degraded in the fuel system before landing. A few results which are available suggest that small amounts of working with the fuel system does not destroy fire resistance. For example, a rocket sled test at RAE indicated that fuel which had had one pass through an aircraft centrifugal pump still had fire resistance. Also, fire tests by Lockheed, Georgia, showed that FM-9 fuel from the main tank and surge box of the C-141 systems rig had fire resistance after 3-1/2 hours of simulated flight. Unfortunately, the Lockheed tests were done using an airgun device which is not as well documented as either the wing spillage or rocket sled. This is an area where more work needs to be done.

BLENDING OF THE ADDITIVE WITH KEROSINE.

How to get the additive into kerosene is a vital matter. FM-9 fuel has non-Newtonian properties and introduction of the additive and carrier fluid at the refinery would introduce virtually insuperable problems in the fuel distribution system. Much effort in the United Kingdom has therefore been directed towards the most satisfactory means of incorporating the additive.

All the antimisting additives studied to date, including FM-9, are high molecular weight polymers and as such they are susceptible to mechanical degradation after dissolution in kerosene. Also, the rheological properties of the modified fuels make them more difficult to filter than kerosene. Because of these properties, the optimum place to introduce the additive is at the aircraft refuelling point. The United Kingdom has therefore concentrated on demonstrating the feasibility of blending in the additive at this point and ensuring that the fuel blend so prepared remains homogeneous. Also, within a short period of time the blend should have developed satisfactory fire suppression properties and be compatible with the aircraft fuel system.

The nature of the blending process is determined largely by the form of the additive itself. FM-9 additive is obtainable in fine powder form and United

The nature of the blending process is determined largely by the form of the additive itself. FM-9 additive is obtainable in fine powder form and United Kingdom studies have concentrated exclusively on high-solid content dispersions of this powder in a carrier fluid. The advantage of dispersions of the FM-9 additive over solutions is that the individual polymer molecules remain coiled up rather than being expanded and overlapping; this gives the dispersion a much lower viscosity for a given polymer content and the additive is much less prone to mechanical degradations while it is in a contracted state.

In optimizing the FM-9 dispersion, several factors limit the choice of a liquid as a carrier fluid for blending FM-9 into kerosene. These are:

1. The carrier fluid should preferably not contain elements which would give rise to new problems of atmospheric pollution or corrosion of engine parts.

2. The carrier fluid should not have too low a boiling point because this could lead to handling problems and could significantly reduce the flash point of the fuel.

3. It is essential that the carrier fluid should be mixable with kerosene to the extent of at least 1 percent by weight within the normal range of fuel operating temperatures.

4. The carrier fluid should not appreciably swell the FM-9 particles, otherwise, the material would become unworkable.

Work on the optimization of FM-9 dispersion has been carried out by ICI, by Shell Research Ltd, and by RAE. Many organic liquids were studied before a suitable carrier fluid was found; likely candidates being severely restricted by the fact that many liquids which cause little or no swelling of FM-9 particles also have low mixability with jet fuels. The final carrier fluid decided upon is a glycol with a small amount of amine added. It is perhaps pertinent to add here that the carrier fluid is not present solely as an inert material. If FM-9 powder only is dispersed in jet fuel at ambient temperature, coagulation and floc formation soon occurs and the swollen additive particles settle. The carrier fluid prevents this by greatly increasing the rate of polymer dissolution.

The FM-9 content of the dispersions is currently fixed at 32 percent by weight; this level being chosen because of the following factors:

1. The FM-9 content should be as high as possible to minimize the amount and cost of carrier fluid being blended into the fuel.

2. The FM-9 content should be high enough to prevent settling of particles during storage. Inhomogeneity and difficulties in metering the material would thus be avoided.

3. If the FM-9 content is too high, then the dispersion will be too viscous to be pumped and metered satisfactorily.

Tests on the dispersions currently used indicate that no significant changes occur after storage at ambient temperature and at -20° C, but some coagulation of particles occurs after storage at +40° C for 3 months.

In addition to work on dispersions, a blender has also been developed for adding the dispersion to kerosene. It must be stressed here, however, that this device was designed for the purpose of demonstrating the feasibility of blending dispersion on a laboratory scale and it is not necessarily representative of what might be used in practice. Polymer particles in FM-9 dispersion begin to swell rapidly on contact with kerosene, but laboratory experiments showed that if the dispersion/kerosene was not well sheared, so as to break up the dispersion and separate the polymer particles, then swelling occurred only at the dispersion/kerosene interface. This produces a coating of swollen polymer gel around the dispersion which hinders dissolution. The blender was therefore designed to give a short period of very high shearing and turbulence immediately after the dispersion has contacted the kerosene, so ensuring separation of all the polymer particles. The blender is shown schematically in figure 7-1.

In this apparatus, aviation kerosene is pumped at a measured rate from a reservoir and the requisite amount of FM-9 dispersion introduced into it just prior to an in-line high speed homogenizer. The dispersion is delivered by a trilobe pump which is set to give the required flow rate. The dispersion/kerosene mix then passes immediately into the homogenizer where it is sheared by a cruciform rotor before being forced through a fine emulsor screen.

Considering the properties of FM-9 fuel so produced, fire resistance has been assessed 15-20 minutes after blending. Tests have been carried out using the RAE rocket sled facility and these have shown conclusively that adequate fire resistance is developed after this period with 0.3 percent FM-9 fuel, provided that the base fuel temperature is not less than -5° C for jet A of 18-20 percent aromatic content or not less than 3° C for fuel of 11 percent aromatic content. One undesirable feature noted in certain cases during these tests was the tendency for the polymer particles to settle out from the blend before they dissolved. This occurred when the fuel temperature was low and/or the aromatic content of the fuel was low. Another undesirable aspect was the difficulty experienced in degrading freshly-blended FM-9 fuel. Here the energy required for degradation is very much higher than for fuel which has been allowed to equilibrate for several hours or longer. Thus, 15-20 minutes after blending, fuel has satisfactory fire resistance but causes serious problems for current mechanical degraders. Both these problems are considered to be caused by slow rates of polymer dissolution.

This degradation effect does, of course, relate only to problems which would be encountered with in-line blending immediately before fuel entered an aircraft. If fuel, so prepared, could be held in a storage tank for several hours and allowed to equilibrate prior to use, then this problem could be avoided, but it would then be necessary to pump modified fuel from the storage tank to aircraft.

Currently, efforts are being made in a number of areas to achieve more rapid dissolution of the additive, and work relevant to the storage tank approach is also being done.

CHANGES NEEDED IN FUEL SYSTEMS AND ENGINES.

Work in the United Kingdom in the late sixties clearly indicated that if antimisting fuels were to be used in aircraft, then some modifications of engines and/or fuel systems would have to be made.

Considering first, the low pressure side of the fuel system, the main components involved here are the tank boost pumps and jet pumps. The former are normally centrifugal pumps and early antimisting fuels gave severe problems with these at low temperature — pumping efficiencies were reduced by an order of magnitude at -40 C. However, FM-9 fuel has pumping efficiencies that are only about 30 percent lower than those for jet A-1 over the temperature range ambient down to -40° C. Also, recent tests indicate that such performance is found for both freshly-blended and equilibrated FM-9 fuel. However, confirming tests are required from a number of pump designs, particularly under low temperature and reduced pressure conditions.

One item which may give problems with tank booster pumps is the possible formation of shear gel around the motor windings. In the BAC 1-11 system and component tests with AVTUR/FM-9, gel was formed in the tank pumps and some other system components and there was a residual drag reduction effect on the pipework. There were a number of reasons that were thought could have contributed to this event. As this gel formation was a potentially serious problem, further tests were made using a similar tank booster pump and fresh in-line blended fuel (30 minutes old) and with factory-made jet A/FM-9/carrier fluid fuel at ambient temperatures. Because of fuel availability, these tests had to be operated on a recirculation basis for periods of about 2 hours (similar to the duration of the BAC 1-11 cruise test). No evidence of gel formation was found in the pump and subsequent recalibration with jet A-1 showed no residual effects on the pipework. Recent work on the HAAKE viscometer, however, has shown that gel was formed increasingly as the temperature was lowered below ambient (20° C). The gel formation was not appreciably influenced by shear in the range 1,000 to 5,000's^{-1}. Work of a contractor to investigate viscous drag around motors has shown no evidence of gel formation at ambient temperature, but gel formation has been found around one of the rig bearings with fuel at -5° C. Screening tests at Shell Research have also shown that the presence of carrier fluid inhibits the tendency to form gel, but that formation can still occur under certain conditions.

Jet pumps appear to be the item most affected by the use of AMK — some show marked reductions in efficiency with FM-9 fuel. There are, however, some inconsistencies in the results, and investigations into possible methods of improving performance are currently being made.

No problems have been found to date with capacitance gauges, and experience with industrial turbine flow meters suggests that providing the flowmeter is handling fuel of a sufficient degree of degradation, no great changes will be required. The main point is that it will have to be located downstream of any degrader. Also, compatibility with rubbers and sealants does not appear to be a problem with those tested in the UK.

Two important items connected with the low pressure fuel system are unintentional degradation and water compatibility. Considering the former, only limited information exists on the extent of unintentional degradation caused by pumps, etc., and that which does exist has not been sufficiently quantified in terms of fire resistance. The limited results available suggest that this may not be too serious a problem but the amount of degradation will depend on the particular fuel system and the fuel management scheme adopted.

Water compatibility has received considerable study in the United Kingdom. If large amounts of bulk water are added to FM-9, an emulsion can be formed,

originating at the interface, which in extreme conditions can block tank boost pump screens and water drain valves. Tests at Shell Research indicated that the solubility of water in FM-9 is much higher than in normal kerosene. The rare event of gross contamination of fuel by water during fuelling will cause major difficulties. In order to ascertain whether sufficient water to cause problems would be ingested or precipitated during flight, FM-9 fuel has been investigated by the use of a flight simulator rig at Shell Research and by two carriage trials with AMK fuel in the wing tip ferry tanks of a Canberra aircraft. Recent tests at Shell gave no water gel, but there were definite indications at the end of the tests that FM-9 fuel contained more water than referenced jet A-1 fuel. In the actual aircraft flight, actual aircraft flight trials, which totalled 57 hours, 43 flights, at both high and low level with a summated descent through clouds of 172,000 feet rigorous inspection of the wing tip tanks has shown no evidence of water gel formation. The fuel was not changed during the test periods and in the second series of trials (36 flights, 46 hours, 147,000 feet cloud descent), the fuel water content increased from 60 parts per million (ppm) weight per volume (W/V) initially to about 200 ppm W/V at the end of the trial. Samples of this fuel passed the standard 2 rocket test after the trial and showed no change in specific power required for degradation.

In a recent series of tests, free water was added to a small tank containing jet A-1/FM-9/carrier fluid fuel and an air rejecting type booster pump with an 8-mesh debris guard. Initially, water was added to give a nominal concentration of approximately 200 ppm. The water droplets sank to the tank base; after 1-1/2 hours there was no sign of emulsion and the tank was pumped out. The debris guard remained clear and the water stayed in the unusable fuel fraction. Increasing quantities of water were added, rocking and stalled operation of the pump being used to provide agitation. At a nominal concentration of 2,000 ppm, some emulsion formed on the pump screen but there was no difficulty in pumping out the tank. As a final test, a water concentration of 38 percent was used. A large amount of emulsion formed on the tank base and the pump screen and in the bulk of the fuel. The tank pump still delivered fuel but the flow-rate may have been reduced. Emulsion remained on the screen and settled on the tank base from the bulk fuel by the next day. Clearly, this last test represents inordinate contamination. Whether the water fuel carried through the booster pump would be broken up by the rotary degrader still remains to be tested, as do any possible effects on filters and control units.

Moving on to the engine area, work on a Spey Phantom engine in 1974 clearly indicated that the engine and its accessories could function correctly, provided that the FM-9 additive in the fuel was degraded prior to use. More detailed work showed that filters, heat exchangers, atomizers, and fuel control systems required varying levels of degradation in order to operate satisfactorily. Much effort has therefore gone into degrader design and into assessing the appropriate levels of degradation required in the components mentioned above.

Early work on intentional degradation done by Shell Research Ltd, showed that a filter performance similar to that of kerosene, could be obtained after four passes through an injector rig (AHEM) at a pressure of 2,600 psi (17.25 MPa) and at a flow rate of about 7 liters/hour. This was known as 4X AHEM fuel and was used for the above Spey engine test at National Gas Turbine Establishment (NGTE). Engine control simulator tests, using fuel from another degrader using diesel injectors, showed that fuel which had received two passes (2XDI) appeared to be satisfactory. However, work on alternative mechanical degraders indicated that fuel with the

A large number of mechanical degraders were investigated at RAE, including spinning discs, nozzles including ultrasonic, vortex generators, rotating cylinders, impellers, magneto-striction, wire screens, etc. These all produced degradation, but not to the level required. The most promising device consisted of a series of holed rotors and stators which produced fuel that was marginally acceptable on the engine control simulator. A number of different internal arrangements were investigated which culminated with the introduction of the "Pelton Stator." This produced a better performance with a reduction of the number of rotors and stators and the specific power. These were known as the D61 degraders. At this stage, difficulties occurred with AMK fuel quality and the design of the D61 was frozen and the units used for quality assessment. To this point, all tests had been made using AVTUR/FM-9.

Two large versions, the D86 and D101, have been made (numeral refers to rotor diameter) and the best performance so far obtained for FR_H (hot filter ratio) of 1.0 to a flowrate of 1.05 litre(s) for a specific power input of 66 $kWsl^{-1}$ for both 20 paper and 16-18 Dutch weave filters using jet A-1/FM-9/carrier fluid fuel. It is relevant to point out here that the level of degradation is assessed by measuring the rate of filtration of degraded fuel, relative to that for kerosene, through a 16-18 Dutch weave filter.

The degraders are operated at a high rotational speed, 10,000 to 15,000 rpm, and it has been shown that specific power appears to be independent of speed, but that the flowrate that can be adequately degraded varies approximately as the speed ratio cubed. These degraders all have a pressure loss.

Another rotary degrader using a different type of rotor and a peripheral stator showed that it was possible to consider a combined pump/degrader unit. It consisted of a two-stage arrangement which for the same filter ratio reduced the specific power input to 45 kW per liler ($kWsl^{-1}$) for a flow of 0.2 litre(s) while giving a pressure rise of 310 kilo pascals (kPa). Demonstration of this unit convinced two equipment manufacturers of the feasibility of a combined pump/degrader and two development contracts have been placed. Testing of the units with AMK at both firms has just commenced, both units are housed within existing engine first-stage pump casings.

Degradation by chemical means is feasible but, in general, a mechanical device is much to be preferred.

The performance of the D61 degrader is sensitive to fuel quality, and data in the literature suggests that any other degrader or degradation in any component will be similarly affected. To date, large variations in degrader power requirements have been experienced, due to changes in additive quality and in aromatic content of the base fuel. Lesser changes have been found with variations in the purity of carrier fluid components.

These effects underline the need for strict quality control in all facets of the production of FM-9 fuel.

Also, as mentioned earlier, freshly-blended fuel is more difficult to degrade than equilibrated fuel. Tests indicate that from 1 to 3 hours is required before an acceptable degree of degradation can be obtained (Filter Ratio = 1.2 on 16-18 Dutch weave filter) with the D61B degrader using a specific power input of 75 $kWsl^{-1}$.

In addition to early tests at NGTE on a simulated control system test rig, more recent tests have been made on the Combined Acceleration and Speed Control Unit (CASC) of the RB 211 engine using jet A/FM-9/carrier fluid fuel. The rig consisted of a TriStar tank boost pump unit, first-stage engine pump, a second-stage gear pump, pressure drop spill control valve, auxillary throttle valve and finally a simulated burner. The normal paper filter between the pumps was replaced by a 20 stainless steel square mesh filter. The AMK fuel as supplied to the tank booster pump was undegraded. During the test, which totalled 1-1/2 hours, four steady-state conditions corresponding to engine idle, cruise, climb takeoff conditions were tested as well as two nominal acceleration/deceleration tests. Finally, a lightup condition was tested. The controlled flowrates were 5 percent lower than with kerosene, the average input power was about 3 percent higher. The acceleration/deceleration results were similar to those expected with normal kerosene. Degradation of the FM-9 in the system was such that standard F.R.of 1.5 to 2.4 occurred at the burner. Two bearing failures occurred which were considered to be due to the lack of lubrication/cooling. The firm were of the opinion that the bearings could be redesigned to operate satisfactorily with AMK.

Atomizer tests using a Simplex nozzle have been made at engine cruise and idle conditions (flow number = 1.0 at pressures of 400 pounds per square inch (psi) and 100 psi, respectively) using fuel of varying levels of degradation. The tests were simple, the quality of the spray being assessed photographically. At the higher pressure (400 psi) sprays of the same cone angle were produced at all levels of degradation, the coarseness of the spray increasing as the level of degradation decreased. At the lower pressure (100 psi), a spray that was considered acceptable was obtained for a specific power input of 38 $kWsl^{-1}$ (T 23° C) with fuel from the D70 degrader. The advantages of power inputs higher than 51 $kWsl^{-1}$ (T 30° C) appeared minimal. The FR value for the 38 $kWsl$ fuel was 1.8 hot/ambient and 6.0 of ambient for a 20 paper filter. (FR = 1.6 standard filter at ambient.)

Sauter mean diameter (SMD) values for three burners have been measured by a contractor. The fuel was degraded to standard FR values of 1.2, 1.18, and 1.49 by the less efficient D61 degrader. The atomizers tested have a pressure jet duple as used in the Spey engine, an airspray as used on the RB 211, and a fan spray as used on the Harrier Auxiliary Power Unit (APU). The conditions covered were representative of engine ground crank, idle, and full load. The SMD values were considered reasonable at all three levels of degradation for the air-spray and fan-spray burners, but the sample FR = 1.49 was thought unreasonable for the duple. Spectral distribution was not assessed and the SMD, which does not always correlate with combustor performance, is only a first order indicator of spray quality.

With regard to heat exchangers, two specialist firms are currently investigating the performance of dimpled tube and flat plate forms of heat exchangers. For dimpled tubes, the fuels used are jet A-1, undergraded FM-9 and FM-9, degraded to FR = 1.2. Three lengths of the tube were investigated and initial analysis indicate that there is an optimum length. At this optimum, there is a loss in heat transfer coefficient of 4 to 13 percent depending upon the flowrate. Under isothermal conditions the increase in pressure drop was of the order of 10 percent. These results are still being analyzed.

In the flat plate programme herringbone, serrated, and plain forms have been investigated with jet A-1, undergraded FM-9 (excepting plain) and FM-9 degraded nominally in the range FR - 1.2 to 1.5. The results are summarized below.

ISOTHERMAL PRESSURE DROP

Sample	FR	+% P relative to Jet A-1
Herringbone	1.2	18%
	1.5	18%
	U*	Up to 35 times greater
Serrated	1.2	22%
	1.6	46%
	U*	Up to 80 times greater
Plain	1.2	11%
	1.5	11%

U* - Undegraded

Note the pressure drop information obtained under heat transfer conditions differs from that quoted above, particularly with undergraded AMK.

HEAT TRANSFER COEFFICIENT

Fuel	Herringbone Sample	Serrated Sample	Plain Sample
Jet A-1	100	100	100
FM-9 FR 1.2	83-91	86-92	87-95
FM-9 FR 1.5	83-91	86-92	83-91
Undegraded	74	80	-

Both firms have experienced difficulties in obtaining repeatable results when subsequently retesting with jet A-1 after using AMK. There being evidence of some fouling as shown by repeated jet A-1 isothermal pressure drop tests. This appears to happen very rapidly and it is not known whether it builds up with time, but we hope to arrange a duration test.

CONCLUSIONS

The results that have been obtained to date indicate that FM-9 additive at a concentration of 0.3 percent offers undoubted benefits from the point of view of increased fire resistance. Also, it is possible, at least in principle, to design a device which will degrade this fuel to a level which is, in the main, compatible with the engine and its components. So far, no insoluble problems have been found which would preclude its use in aircraft, but there are a number of areas which give significant concern, and they are listed below.

1. Problems remain on how to introduce the additive into base fuel. In-line blending, immediately prior to the aircraft, brings both the difficulty of degrading freshly-blended fuel and the effect of base fuel with low aromatic content and/or low temperature. Blending of the additive further upstream is still essentially an unknown quantity.

2. The necessity of maintaining a high standard of quality control.

3. While single pass mechanical degraders can be made, further development will be required to reduce specific power consumption, because this could create some fuel temperature problems.

4. Unwanted degradation in the low-pressure fuel system needs to be quantified and its effect on fire resistance determined.

5. Some fuel system components, including heat exchangers and jet transfer pumps, may need to be modified.
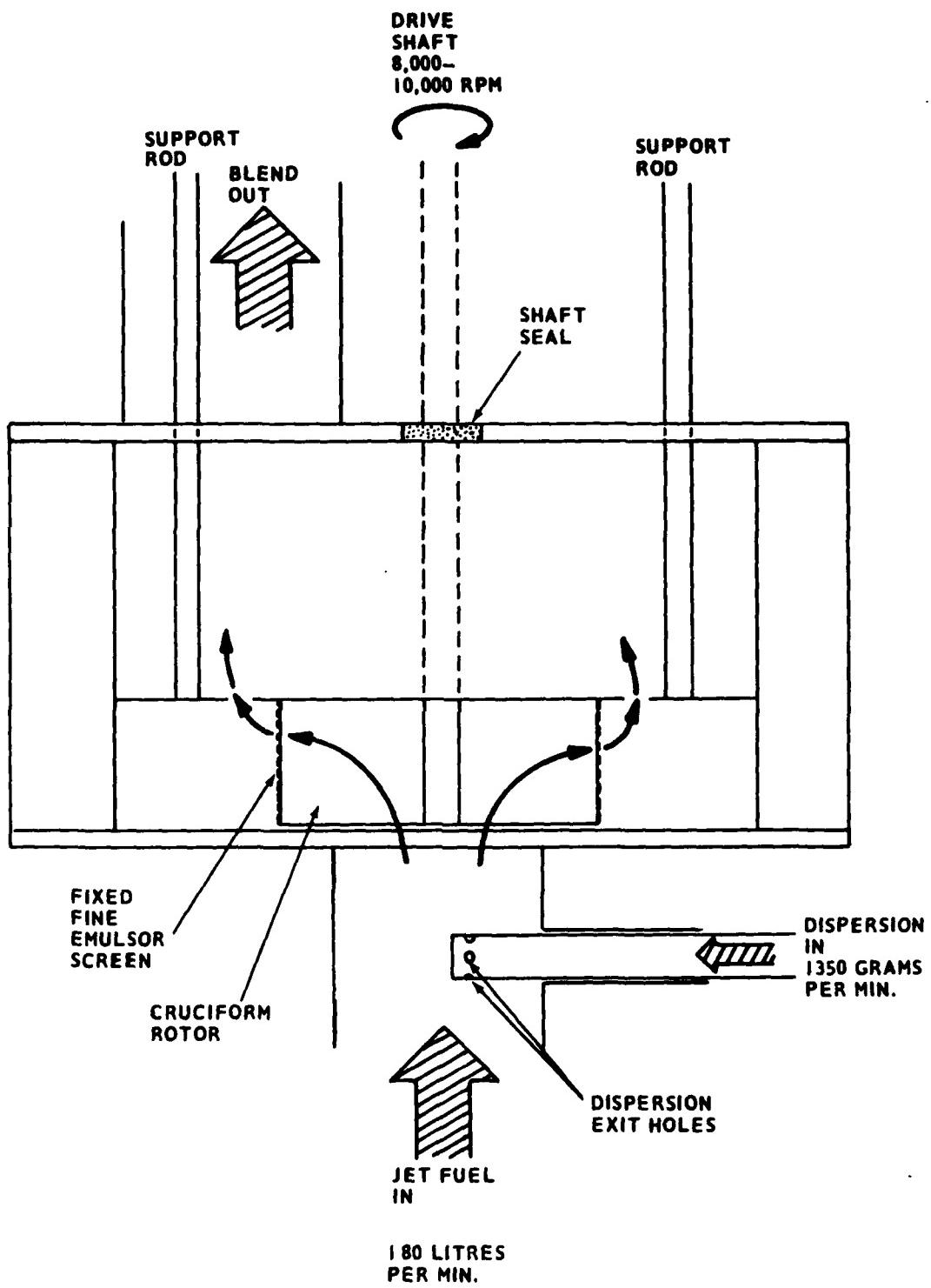
FIGURE 7-1. A DEVICE FOR THE BLENDING OF ANTIMISTING ADDITIVE DISPERSION
INTO AVIATION KEROSENE

Questions and answers following "UK Antimisting Kerosene Research"

Discussions:

Mr. Fiorentino: Pratt and Whitney Aircraft. You mentioned early in your talk that you had a problem with impurities at very low concentrations. Can you tell us what they were and has anyone looked at what effect some of the additives that we put into fuels might be on the degradation qualities of the fuel or on the performance of the fuel?

Mr. Wilford: The jet A, jet A-1, and other fuels that the additive is being put into, already contain all the additives that are put into these fuels. I don't think there's going to be any particular compatibility problem there.

Mr. Fiorentino: I'm not sure that we don't add additional additives at certain airports after the fuels are delivered to the storage tanks.

Mr. Wilford: What sort of additives?

Mr. Fiorentino: Antirust.

Mr. Wilford: We have certainly looked at fuel containing fuel system icing inhibitor and also High Tech E 515 which, I think, is a pipeline corrosion inhibitor and that certainly had no adverse effect.

Mr. Fiorentino: One other comment. I would agree with your results for SMD as a function of the F.R. but I would caution you that we did find differences in the distribution of a spray, although the SMD got better as the fuel was processed or degraded. We did find changes in the pattern which could affect temperature coming out of the burner, radial profile, and those kinds of things.

Mr. Wilford: Was the difference in flow distribution across the cone?

Mr. Fiorentino: Yes

Mr. Brammer: Westland Helicopters, England. I have an impression from this discussion about changes to both the engine and the aircraft fuel system that it's a very significant redesign to accommodate this fuel additive. In fact, the booster pump efficiency is down between 10 and 50 percent. The jet pumps suffer a very significant performance loss and may need to be redesigned. Even if that is practical, there is a vent compatibility problem where the existing vents on a lot of airplanes will sense a failure in the pressure refueling system. In fact, they're adequate enough to allow overboard venting without damage to the system. My impression is that it would be a significant redesign of the fuel system with a fairly comprehensive requalification test on each aircraft type to requalify for the use of these antimisting kerosenes. I wonder if you would comment on this.

Mr. Wilford: Obviously, it's very difficult to give a precise answer to that. A combined pump degrader unit to replace an existing pump of the same physical size, though it will use more power, may overcome the engine side of the problem with regard to the low-pressure fuel system. The figures shown for the reduction in pumping efficiencies probably are maximum valves, those that are obtained with a not particularly representative pump. Some other tests do suggest that the drops

in efficiencies will not be as bad as that. Perhaps the worst possible case is jet pumps. There are difficulties. I don't think anybody could deny that, but I believe there are possibilities of doing redesigns here that may make these satisfactory.

Mr. Westfield: We are at least three and a half years away from deciding whether or not this fuel can be used. I think in three and a half years we can do considerable work on the problems you mentioned. I can assure you we will make every effort to assure the changes are minimal.

Mr. Kessler: U.S.Air. You mentioned in your presentation the laboratory fuel could be blended at the speed of 50 gallons a minute. We fuel aircraft at a higher speed than that today. Is this a limitation for blending or can this additive be blended at a more rapid rate.

Mr. Wilford: I feel sure that it could be blended at a more rapid rate if given the correct designed equipment. The 50 gallons per minute was just the limits of the particular rig or device that we put together with off-the-shelf items.

Mr. Kessler: Second question, with regard to compatibility with other additives, has any work been done to test compatibility with an additive that is designed to suppress microbe growth in fuel?

Mr. Westfield: That is a very specific item in our program.

Mr. Livermore: British Aerospace. You said that some work has been done that shows coelastomers are not particualrly affected. There are a large number of other nonmetallic materials such as modified Dions, BME, and fiberglass now being used in airplane fuel systems. Can we have some assurance that this will be investigated as part of your program?

Mr. Wilford: I would see no problem in arranging to test these materials.

Mr. Livermore: There is another question and that is with regard to the carrier fluid. I remember that an anti-icing additive used a few years ago, contained a small percentage of glycol in companion with methyl cellosolve. And the problems associated with the effects in the air frame fuel system were such that the glycol had to be removed and you now only use methyl cellosolve for an antiicing additive. Is there any reason to suppose that your use of this material will not have the same peculiar behavior patterns that the 55MB had? I think you might find that the microbes were rather liking the glycol.

Mr. Crowther: British Airways. I'd like to know if any effort was made to find a carrier additive with a reasonable calorific value to replace the fuel that it will replace in the tank on a 747? It would be carrying over a ton of additive. Is this useful in terms of heating value or not?

Mr. Wilford: The fuel containing carrier and additive is within the current specifications for calorific value. The carrier fluid is primarily glycol which is carbon, hydrogen, and some oxygen. Because of the oxygen, there is calorific value, and it will not be quite as high as it would have been if it was solely carbon and hydrogen, but any reduction in calorific value would be absolutely minimal.

Mr. Franz: You say that you have a new unit that is being run as part of an aircraft engine pump?

Mr. Wilford: There are two degrader units that are combined pump degrader units being built by two different component manufacturers. They have modified existing pumps to become pump degrader units incorporating a rotor and peripheral stator. Testing of these has commenced literally within the last week or so. We hope they will perform as well as the other degraders we've had.

Mr. Franz: Do these units still have the same high rotational speed requirement?

Mr. Wilford: Yes, on the order of 10,000 rpm, I believe.

FUNDAMENTAL STUDIES OF ANTIMISTING FUELS

BY

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ABSTRACT.

Research is currently being undertaken to determine the various physical character-
istics of antimisting fuel. It is an endeavor to prevent postcrash fuel mist
fires. The following studies were done: (1) drop and jet breakup studies using an
image processing technique, (2) flammability of fuel mist under simulated airplane
crash conditions, (3) skin friction measurements, (4) determination of the tensile
viscosity of non-Newtonian antimisting fuel as a function of the extensional rate,
and (5) water compatability measurements. The results indicate that the mechanism
which prevents antimisting fuel breakup is related to the time-dependent tensile
viscosity of antimisting fuel under stress. Drag reduction phenomenon was also
observed at Reynolds numbers higher than 2×10^4. Uptake of water by the anti-
misting fuel is higher than that for the neat fuel. In addition, its rate of
absorption depends on the concurrent degree of agitation.

INTRODUCTION.

Fundamental studies on the antimisting fuels are being conducted to prevent the
ignition of fuel during a survivable aircraft crash landing. When an aircraft
crash-lands, fuel tanks generally rupture and a large amount of fuel is spilled.

The fuel that is spilled while the aircraft is still in motion encounters aero-
dynamic forces. Under these conditions, conventional aircraft fuel rapidly breaks
down into droplets creating fine mist. Due to the presence of heat sources, such
as hot engine parts, engine exhaust gases, and heat and sparks generated by
friction caused by aircraft motion along the ground, the spilled fuel can easily be
ignited. Thus, a survivable aircraft crash landing can become a major disaster
because of the potential fire hazard.

One way to decrease mortality of the crew and passengers from the survivable
postcrash fires is to use a high molecular weight antimisting polymer in the
aviation fuel. Certain polymeric additives have been shown to prevent misting and
fireball formation when the fuel is subjected to external forces and ignition, as
in violent fuel tank rupture. These long-chain molecules of antimisting polymers
have time-dependent rheological properties, including tensile viscosity and shear
thinning and thickening, which make antimisting fuel breakup complex as compared to
neat Newtonian fuel. Little is known about the basic mechanism of antimisting fuel
breakup and the rheological characteristics responsible for inhibiting its breakup.
However, an understanding of the physical characteristics responsible for atomizing
the fuel under dynamic impact release conditions is essential for evaluating a
suitable polymer. Furthermore, techniques to quantify an antimisting fuel mist
need to be developed to determine the influence of the polymer concentration,
temperature, dynamic loading, etc., on the flame propagation mechanism.

In addition, the antimisting fuels must be compatible with the aircraft and engine fuel systems. How antimisting polymers influence the flow through various components of the aircraft, and convective heat transfer characteristics, as well as component effect on the polymer, viz., shear degradation must be understood before this fuel can be used in an aircraft fuel system. Also, efficient methods that restore (degrade) antimisting fuel and determine the degree of fuel restoration (degradation) are needed before antimisting fuel is injected into the combustion chamber of an engine. The above information is vital to a study made to assess the potential antimisting fuel application in current aircraft fuel systems for suppressing aviation postcrash fires.

A combined experimental and analytical study has been undertaken at the Jet Propulsion Laboratory to determine the changes in flow behavior, mist characteristics, pressure losses, compatability with water, etc., which may result because of the use of antimisting fuel as compared to neat jet A. Unless otherwise stated, the experiments discussed below were performed with jet A containing antimisting FM-9 additive developed by ICI.

EXPERIMENTAL RESULTS AND DISCUSSIONS.

A summary of the key technological problems encountered with antimisting fuels is presented in figure 8-1. They have been broadly divided into three areas: (1) non-Newtonian fluid and heat transfer, (2) polymer related problems, and (3) flammability and combustion. The underlined problems in figure 8-1 are currently being investigated and are discussed below.

1. Drop and Jet Breakup. To get a better physical picture of the antimisting fuel breakup, small-scale laboratory experiments were performed in a vertically oriented wind tunnel. This facility has provisions for generating various size drops. The free-stream velocity in the wind tunnel can be varied from 14 meters per second (m/s) to 75 m/s (150 knots). Typical results indicating the modification in breakup of a drop of jet fuel containing the antimisting polymer in jet fuel can be visualized in figure 8-2. Influence on fuel breakup of antimisting additives, AM-1, developed by Conoco and FM-9 were investigated. These pictures of the drop breakup were taken under identical flow and geometrical conditions. As is evident in this figure, the neat fuel drops breakup into a fine mist, whereas the fuel with the polymer additive tends to be inhibited in its formation into smaller droplets. The non-dimensional Weber number $W_e = \rho V^2 R/\sigma$ which influen-s the deformation and breakup pattern of the drop was approximately 48, where ρ is the fluid density, $V\infty$ is drop velocity relative to the environment, R is drop radius, and σ is the surface tension. From previous references (1 and 2) for $W_e > W_{ec}$, the drop remains spherical in nature and oscillates about its mean position. For Weber numbers of $0.1 < W_e < W_{ec}$, the drop breakup is a "bag type mode" where W_{ec} is the critical Weber number. For $W_e > W_{ec}$, the droplet breakup is a "shatter mode." Figure 8-2 indicates a typical shatter mode droplet breakup pattern of the jet A fuel. The critical Weber number in the present investigation was observed to be around 20.

To further enhance our understanding of how these polymer additives modify a fuel breakup, experiments were performed to look into the breakup pattern of a fuel jet with and without the presence of freestream flow (reference 3). A photograph of a capillary jet flow of diameter 0.88 mm and fuel velocity of 3.2 m/s, with and without the presence of the additive, is shown in figure 8-3. It should be recalled that under these flow conditions, axisymmetric, inviscid oscillations are

set up which are primarily controlled by the surface tension. The disturbance which has a wavelength of approximately 4 to 5 times the initial diameter grows the fastest and breaks up the jet into droplets. It should be noted in figure 8-3 that the most ustable wavelength of jet A as well as for fuel containing FM-9 additive is of the order of 4 to 5 times the jet diameter. It is clear also from figure 8-3 that the jet is most unstable to the axisymmetric perturbations. Whereas, AM-1 tends to completely suppress the growth of these unstable perturbations, FM-9 is slightly less effective.

The influence of antimisting polymers on jet breakup in a moving airstream of velocity $V_\infty = 27$ m/s is shown in figure 8-4. The presence of polymer in jet fuel dramatically modifies the jet breakup, and is very effective in inhibiting the fuel breakup into droplets. The breakup pattern was also photographed further away from the nozzle exit. As one would expect, most of the breakup occurs very close to the nozzle exit. The fuel is accelerated very rapidly by the freestream flow and reduces the relative velocity between the fuel and the airflow which is the principal cause of jet or droplet breakup.

From the drop and jet breakup studies, it is quite evident that antimisting polymers are effective in retarding the breakup of the fuel. Further results on the influence of antimisting polymer on aviation fuel breakup are discussed in reference 4. As will be discussed in the following section, this resistance to mist formation, under sudden deformation occurs because of the development of high tensile viscosity.

2. Non-Newtonian Fluid Behavior. One of the ways to represent the flow behavior of an antimisting fuel is shown in figure 8-5. In this figure, the flow resistance has been plotted as a function of straining rate. The antimisting fuel behavior can be divided into three regions.

    a. Handling and aircraft fuel system management region.
    b. Fire protection region.
    c. Engine operation region (restoration of fuel).

The acceptable antimisting fuel should behave during transporation, airport handling, and in an aircraft fuel system similar to the Newtonian jet A. But under straining (deformation) rates encountered in aircraft crash conditions this fuel should provide a large resistance to deformation and hence, suppress the rapid breakup of fuel into a fine mist. The same fuel, however, should also be restorable by some efficient means to a fuel with characteristics close to jet A for normal combustion in an engine. A successful antimisting fuel should have the above behavior over a wide range of environmental temperatures encountered during an aircraft flight. Furthermore, the antimisting additive should not influence the compatability with materials in the fuel-handling system and fuel temperature stability. It should be nonpolluting and nontoxic in nature. Above all, this additive should be economical to produce in large quantities.

In figure 8-5, broken lines indicate the ideal behavior of the antimisting fuel outside the regions from where fire protection is required. Experiments were performed to determine the actual fuel response under stress in this region.

Studies to determine the mechanism which prevents mist formation and consequently its ignition during a survivable crash landing have been performed. These results indicate that antimisting fuel resistance to sudden deformation is related to the

development of time-dependent tensile viscosity (maybe a viscoelastic phenomenon) even though the shear viscosity may not be markedly affected. The dependence of this tensile viscosity was made by studying a tubeless syphon flow and has been discussed in detail in reference 5. The extensional flow measurements could not be made on fuel containing FM-9 additive utilizing this technique. This may have resulted because of the Newtonian behavior of fuel below a critical flow rate (in which case it could not form a liquid column) or the fuel might have gelled, and a column would not form because the flow ceases. It can be seen in figure 8-6 that the onset of non-Newtonian behavior of antimisting fuel, i.e., a large increase in the tensile viscosity with extensional rate or decrease in shear viscosity with shear rate, is associated with a characteristic deformation rate. For FM-9, the characteristic deformation rate can be determined by other methods such as cone and plat shear and (less precisely) pendant drop. It is believed that the mechanism which prevents mist formation is associated with the development of high tensile viscosity under stress as shown in figure 8-6. Because of the relationship of the critical shear rate V_c to the onset of viscoelastic behavior of antimisting fuel, small scale experiments and devices are being investigated to quantify the fire suppression characteristics of such a fuel. It is known that V_c is related to the characteristic velocity V_c above which mist ignition occurs in intermediate- and large-scale using wing shear ignition facility (reference 7).

3. Skin Friction Coefficient. Preliminary experiments to determine the skin friction coefficient as a function of Reynolds number were performed with and without the presence of antimisting additive FM-9 in jet A. These measurements were made between solvent Reynolds numbers (jet A viscosity used to define Reynolds numbers) from 2×10^2 to 2.4×10^4. All experiments were performed at 20° C room temperature. The experimental results of skin friction coefficient with jet A as working fluid collapsed close to a curve predicted and shown in figure 8-7 and given by the following:

laminar region $\quad C_f \qquad = 16/R_e$
turbulent region $\quad C_f^{-1/2} \quad = 4 \log (R_e \, C_f^{1/2}) - 0.4$
(Prandtl-Karman)

For antimisting fuel, the skin friction coefficient C_f versus Reynolds number data lies parallel to the 16/R line in the laminar region. The transition region starts at a Reynolds number of about 2000 and ends at approximately 3500. For Reynolds numbers greater than 3500, the skin friction coefficient decreases rapidly with the increasing Reynolds numbers of and falls under the Prandtl-Karman curve for Newtonian fluids at a Reynolds number of 1.8×10^4. This Reynolds number, beyond which drag reduction occurs, is called the threshold Reynolds number. As reported in reference 6, viscosity has only a minor effect on the increase of the sub-layer thickness which is assumed to be the main factor responsible for the drag reduction. Therefore, drag reduction in antimisting fuel is possible, even though its zero shear viscosity is approximately 2 times that of jet A at ambient room temperature.

These results suggest that an aircraft fuel system operating with Reynolds numbers in the range of $10^4 - 10^5$ with 0.3 percent FM-9, will not require any extra pumping power to transport fuel. Moreover, present results even suggest a drag reduction behavior of antimisting fuel beyond Reynolds number 1.8×10^4, where less power will be needed than required to transport jet A. It should be mentioned that scaling laws for non-Newtonian fluids are not established satisfactorily. Therefore, experiments are being carried out to determine the manner in which this drag reduction region is influenced for flows through tubes of different sizes.

In the present study, unintentional degradation was also observed for fuels collected after the test at Reynolds numbers higher than 10^4. This degradation was measured in terms of time taken to pass through a 12μ filter paper. Under identical flow conditions, a filter ratio (antimisting fuel to jet A flow time) at Reynolds numbers of 2.4×10^4 was 15 as compared to a filter ratio of 33 for undegraded antimisting fuel.

4.   Influence of Liquid Water.   The FM-9 antimisting additive package consists of FM-9 powder and a carrier fluid containing glycol and amin.   Experiments were performed to determine the uptake of liquid water in antimisting fuel and to determine the influence of water on the glycol present.   Water (10 percent by volume) was added to antimisting fuel to form a layer at the bottom of a container 10 x 5 cm) at ambient temperature.   The antimisting fuel was gently mixed for 5 seconds before samples were taken for spectra analysis by Fourier Transform Infrared (FT-IR) at various periods of time.   The spectrum of untreated antimisting fuel was subtracted from each spectrum of the water-treated fuel samples to obtain subtracted spectra which correspond to the changes occurring, due to the presence of water.   It was observed that in less than 20 minutes the water at the bottom of the container preferentially extracts 36 percent of the glycol present in antimisting fuel and in less than 48 hours extracts all the glycol present (figure 8-8).

Each of the carrier-fluid constituents have been added for a specific purpose in the antimisting fuel.   The role of glycol in the carrier fluid is to prevent coagulation while in the carrier fluid, and to increase the FM-9 particle dissolution rate.   It is anticipated that addition of glycol destroys fire resistance, therefore, amine is added to the blend to restore the fire resistance.   The fast and drastic reduction of the amount of glycol in the fuel, because of the presence of water, can explain to some extent the enhancement of fire resistance of antimisting fuel after contact with larger amounts of water as observed in the fire tests performed at JPL.

Preliminary fire tests were done on AMK (0.3 percent) after a 5-minute wash with water and some increase in the fire resistance was visually observed.   However, the same test was done on fuel containing 0.1 percent FM-9 and no change in the fire resistance was observed between treated (washed) and untreated fuel.   Further work will be done in this area with more accurate measurements of the fire temperature and longer water-exposure times.   In addition, we have ongoing experimental work on the influence of various levels of water on emulsion (or precipitate) formation using undegraded antimisting fuel, restored (degraded) fuel and on antimisting fuel during degradation.

The experiments to determine the uptake of water were conducted using the Karl-Fisher and infrared spectrometry techniques.   The series of experiments were performed at 12° C and at 22° C.   Results are shown in figure 8-9.   Comparison of the two sets of data show that at the lower temperature the water absorption in the antimisting fuel is slower (figure 8-9) and the rate of glycol removal by water is reduced (figure 8-8).   As can be observed in figure 8-9, antimisting fuel containing FM-9 additive can absorb water up to 0.13 percent (1300 ppm) as compared to neat fuel which can absorb water in the range of 0.003-0.01 percent (30 – 100 ppm) depending on temperature.   It was further observed that with the increase of the water content in the samples there is a dramatic increase in the cloudiness of the fuel.   No significant change in the transparency of the samples was observed if the samples were allowed to settle, even for several months.

It should be noted that the FM-9 polymer has affinity for water and it can act as an emulsifying agent for water in the fuel. Based on this information, it may be argued that the cloudiness in the fuel can be caused by fine particles of FM-9-H$_2$O coming out of the solution, or the existence of a fine emulsion of water in the fuel.

The investigation further indicated that the amount of dissolved water depended critically upon the external agitation. The above water absorption limits, therefore, should be taken with caution since they represent the extreme upper limits. In actual circumstances, the amount of water which gets absorbed will depend upon the local agitation conditions and agitation time.

Experiments are being continued to determine what happens to this dissolved water when the fuel temperature is lowered. Whether the classical water precipitation from fuel occurs or not will be determined. Influence on the power required to degrade the AMK with various degrees of absorbed water will also be determined.

FLAMMABILITY OF ANTIMISTING FUELS.

The fluid dynamic mechanisms that affect the atomization and the flammability of antimisting fuels during an airplane crash are listed in figure 8-10. A mini wing-shear facility, sketched in figure 8-11 was utilized to simulate the aerodynamic breakup of fuel during a crash landing.

Fuel in this facility is spilled through a rectangular slit of approximately 0.5 cm opening in the wing-tank. The fuel is supplied to the wing-tank from the main 4-gallon pressurized tank. The fuel can be heated up to a temperature of 120° F.

A thermocouple in the wing-tank measures the fuel temperature before the fuel is spilled from the wing. This wing is located in the potential core of an 8-inch diameter free-jet airflow. Air velocities up to 80 m/s can be attained in this free-jet flow. To vary the fuel ejection velocity from the wing, the main tank is pressurized up to 30 psig. A fuel ejection velocity as high as 15 m/s can be attained in this facility. The ignition source in this setup is a continuous oxy-actylene flame. Various sizes of flame holders can be used to vary the intensity and strength of the ignition source. The mass flow to this ignition source is monitored and used to determine the rate of heat release in the airflow. Figures 8-12 and 8-13 indicate the ignition of jet A and antimisting fuel under identical flow conditions. It is evident that, whereas jet A gives a big fire, antimisting fuel is very effective in suppressing the mist formation and its ignition.

Flame temperature distributions along the blower centerline are being measured with an array of four CR-Al thermocouples and some preliminary results are shown in figure 8-14. X is the streamwise distance from blower exit and D is the diameter of the blower. The temperature rise has been scaled by the fuel/air mass flow ratio, where C_p is the specific heat of air and Q_c is the heat content of jet A. Temperature distributions are shown for three different fuel/air ratios for jet A and for 0.1 percent FM-9. For both fuels, the reduced temperature increases with fuel/air ratio, and the location of the peak temperature moves downstream. There is a sudden increase in the reduced temperature for AMK with mAMK/m air greater than 0.1 and this may be utilized to define the boundary between pass and the fail mist configuration. Experiments are being continued to define the fuel mist quantitatively by applying the image enhancement technique on fuel breakup pictures.

Discussion of this technique follows.

Image Enhancement Technique for Mist Evaluation. An image enhancement technique is being developed for evaluating critical mist parameters such as droplet size and distribution, surface to volume ratio, fuel loading, etc., to determine the relative flammability of antimisting fuel mists, and to resolve which parameters influence flame propagation in the mist. A working methodology has been developed which includes droplet illumination, recording, digitization, and subsequent software processing. Figure 8-15 indicates the various steps involved in the image enhancement and analysis technique to get quantitative information on a fuel mist. A pair of antimisting fuel breakup images using the mini wing-shear facility and representing pass (0.3 percent FM-9) and fail (0.2 percent FM-9) conditions are indicated in figure 8-16. The flow of air in these pictures is from left to right. The breakup of the antimisting fuel was taken by sheet-lighting the flow with a 0.3 second duration spark source. This time is fast enough to "freeze" the flow-field.

Since the image is in digital form, intensity thresholding would automatically remove the predominant background. This has been done to the set of photographs shown in figure 8-16 and indicated in figure 8-17. As is evident, much clearer definition of fuel droplets was achieved by thresholding the original photographs (figure 8-16). Figure 8-18 indicates the information shown in figure 8-16 in analog form for the mist terms as pass and fail in the mini wing-shear test facility. These plots indicate the light intensity along a line in the fuel breakup pictures. As is evident, below the threshold lines in figure 8-18, relatively more spikes of intense light sources (thus, large amounts of small fuel particles) were observed in the fail case as compared to the pass case.

In the image processing technique to investigate droplet breakup, a small subsection can also be investigated as shown in figure 8-19. The top picture corresponds to a subsection of figure 8-16 for a pass condition and the bottom to fail conditions. By giving varied colors to different intensities of light in an image (figure 8-19), it was possible to define the boundaries of particles.

Much work is being performed to develop the processing methodology consisting of statistical characterization of the fuel mist. This technique will quantify a dense fuel mist with particles of various shapes and sizes. This information will be valuable in determining the relative fire suppression of various polymers and the combustability of sprays from engine fuel nozzles.

CONCLUSIONS

The main conclusions of this investigation are as follows:

1. The mechanism which prevents mist formation and its ignition during a survivable crash landing is associated with the development of non-Newtonian behavior and time-dependent tensile viscosity for antimisting fuels under stress.

2. A drag reduction region was observed for pipe flow Reynolds numbers higher than 2×10^4.

3. Uptake of water in antimisting fuels is higher than in jet A and its rate of absorption depends on the degree of agitation present.

8-7

ACKNOWLEDGEMENTS

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NON-NEWTONIAN FLUID (RHEOLOGY) AND HEAT TRANSFER	POLYMER RELATED PROBLEMS	FLAMMABILITY AND COMBUSTION
●RHEOLOGICAL BEHAVIOR ●CHARACTERIZATION ●HEAT TRANSFER ●ENGINE SYSTEM COMPATABILITY ●AIRCRAFT FUEL SYSTEM COMPATABILITY ●FUEL SYSTEM INSTRUMENTATION	●WATER COMPATABILITY ●BLENDING ●SHELF-LIFE ●BROAD-CUT BASE FUELS ●MATERIAL COMPATABILITY ●COST EFFECTIVENESS	●FIRE PROTECTION ●COMBUSTION ●FUEL RESTORATION

FIGURE 8-1. TECHNOLOGICAL PROBLEMS ENCOUNTERED WITH ANTIMISTING FUELS

JET-A + 0.1% FM-9

JET-A + 0.1% AM-1

FREESTREAM VELOCITY 35 m/sec
INITIAL DROP DIA 0.26 cm
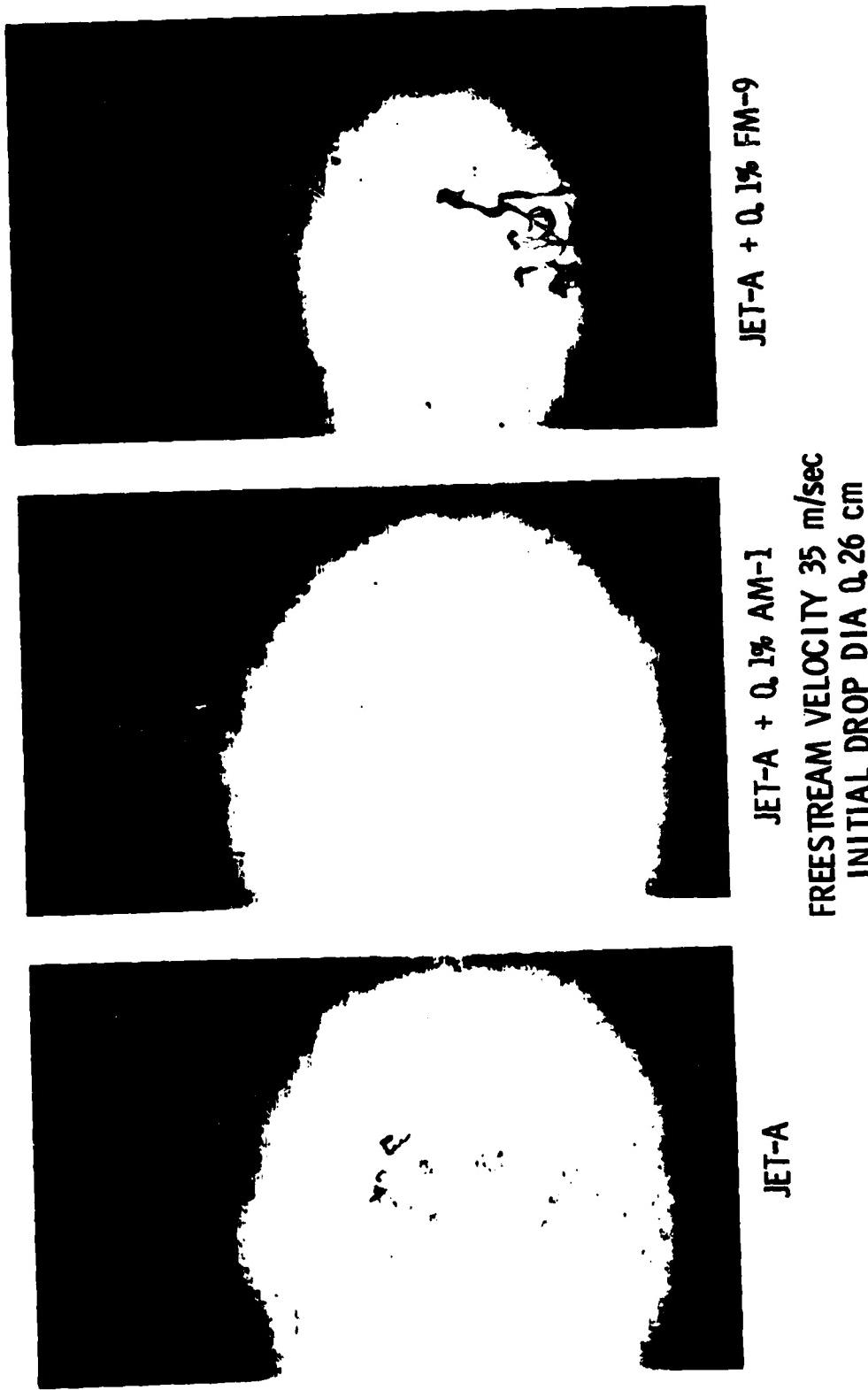
JET-A

FIGURE 8-2. "SHATTER MODE" DROPLET BREAKUP PATTERN OF JET A FUEL
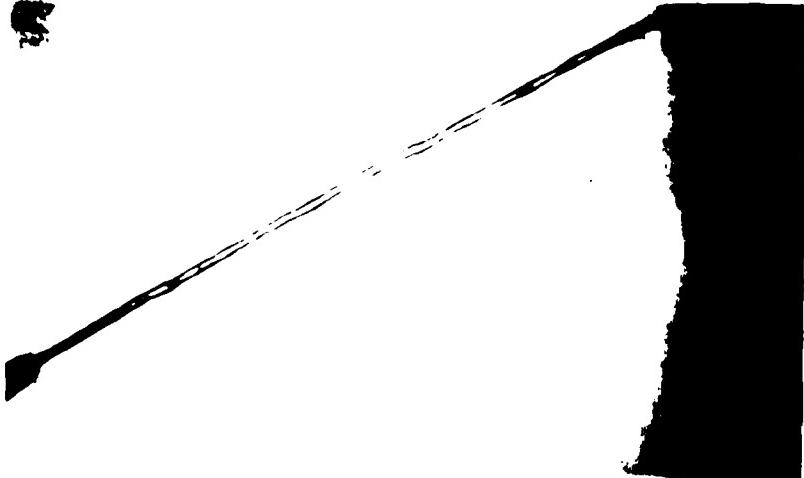
JET-A + 0.3% FM-9
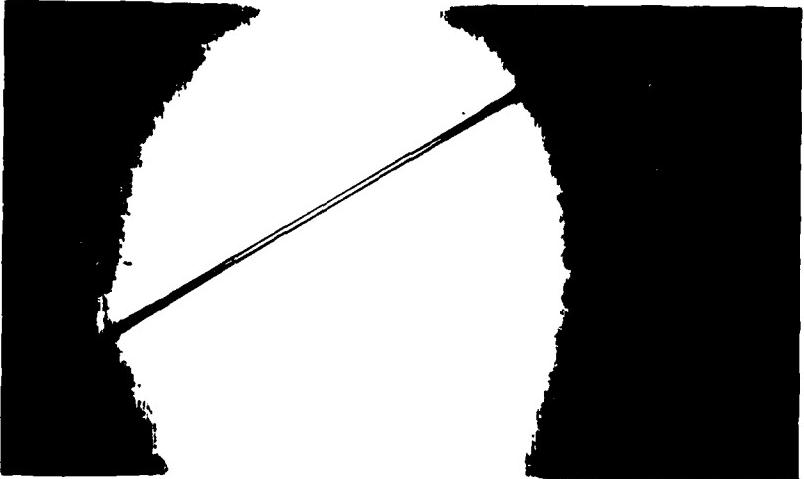
JET-A + 0.3% AM-1

NOZZLE FLOW DOWNWARDS
ZERO FREESTREAM VELOCITY
JET EXIT VELOCITY 3.2 m/sec
JET EXIT DIA 0.88 mm
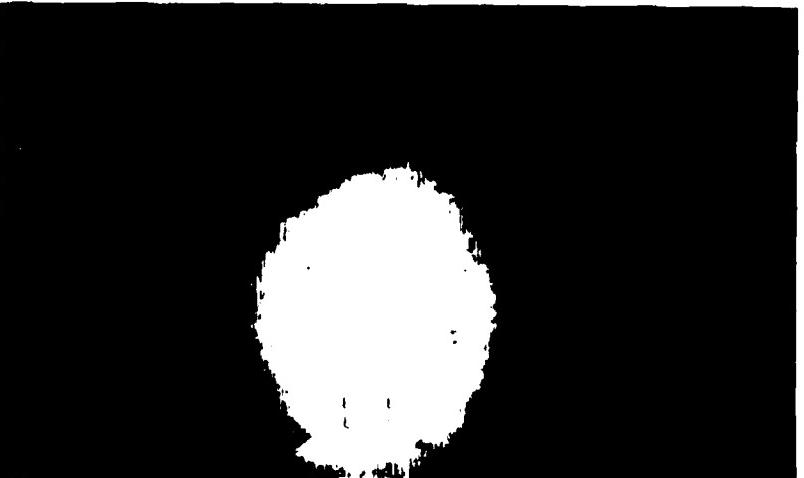
JET-A

FIGURE 8-3. CAPILLARY JET FLOW OF THE VARIOUS FUELS

JET-A
AM-1 0.3%

JET-A
FM-9 0.3%

FREESTREAM VELOCITY 27 m/sec
JET EXIT VELOCITY 3.2 m/sec

JET-A

FIGURE 8-4. VARIOUS FUELS BREAKUP IN A MOVING AIRSTREAM

FIGURE 8-5. ANTIMISTING FUELS BEHAVIOUR
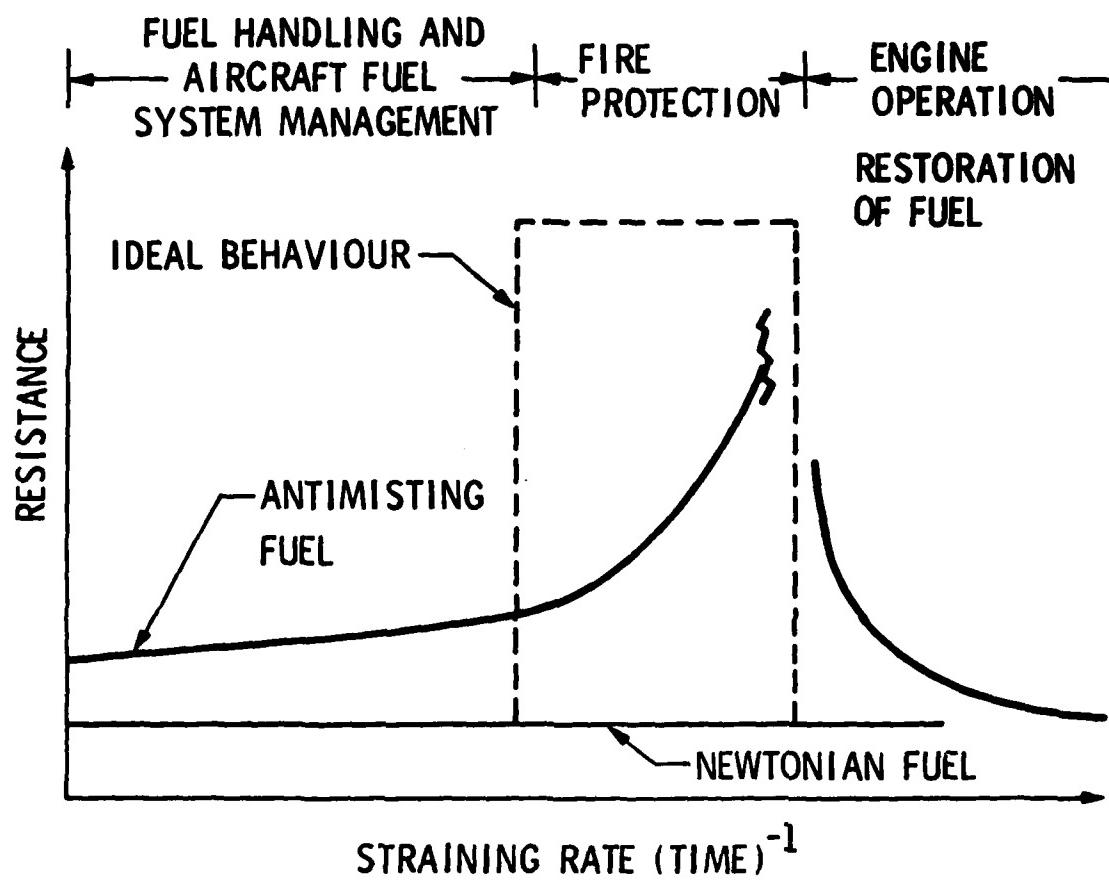
ANTIMISTING BEHAVIOUR DEPENDS ON

- TEMPERATURE
- CONCENTRATION
- INITIAL CONDITIONS I.E., PRESHEAR

8-14
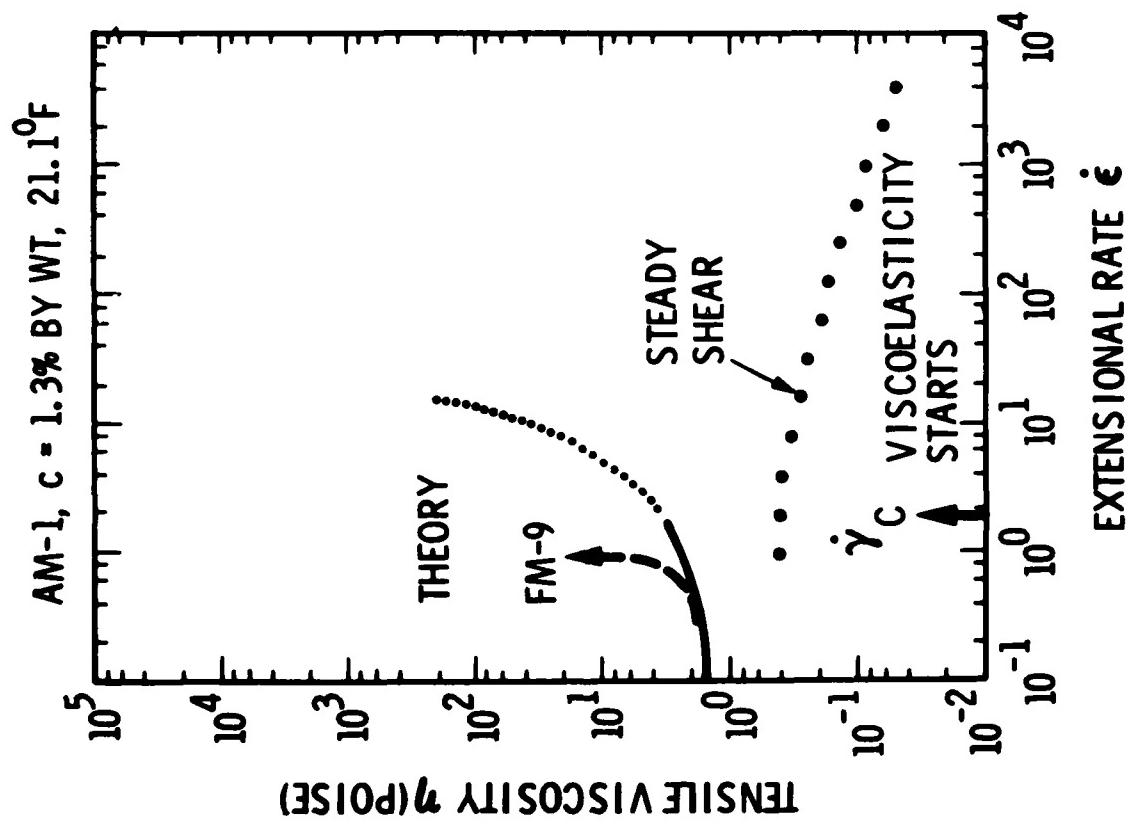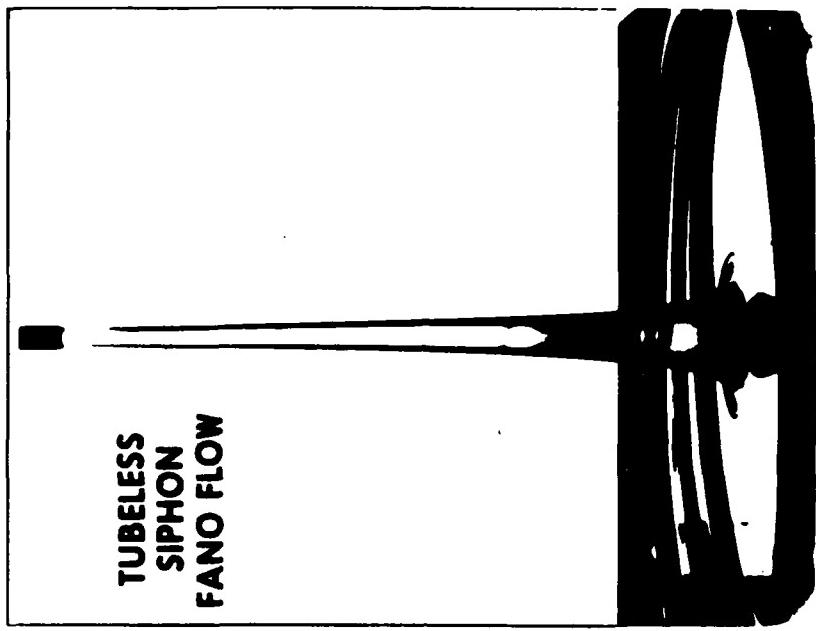
FIGURE 8-6. VISCOELASTIC BEHAVIOUR OF AMK
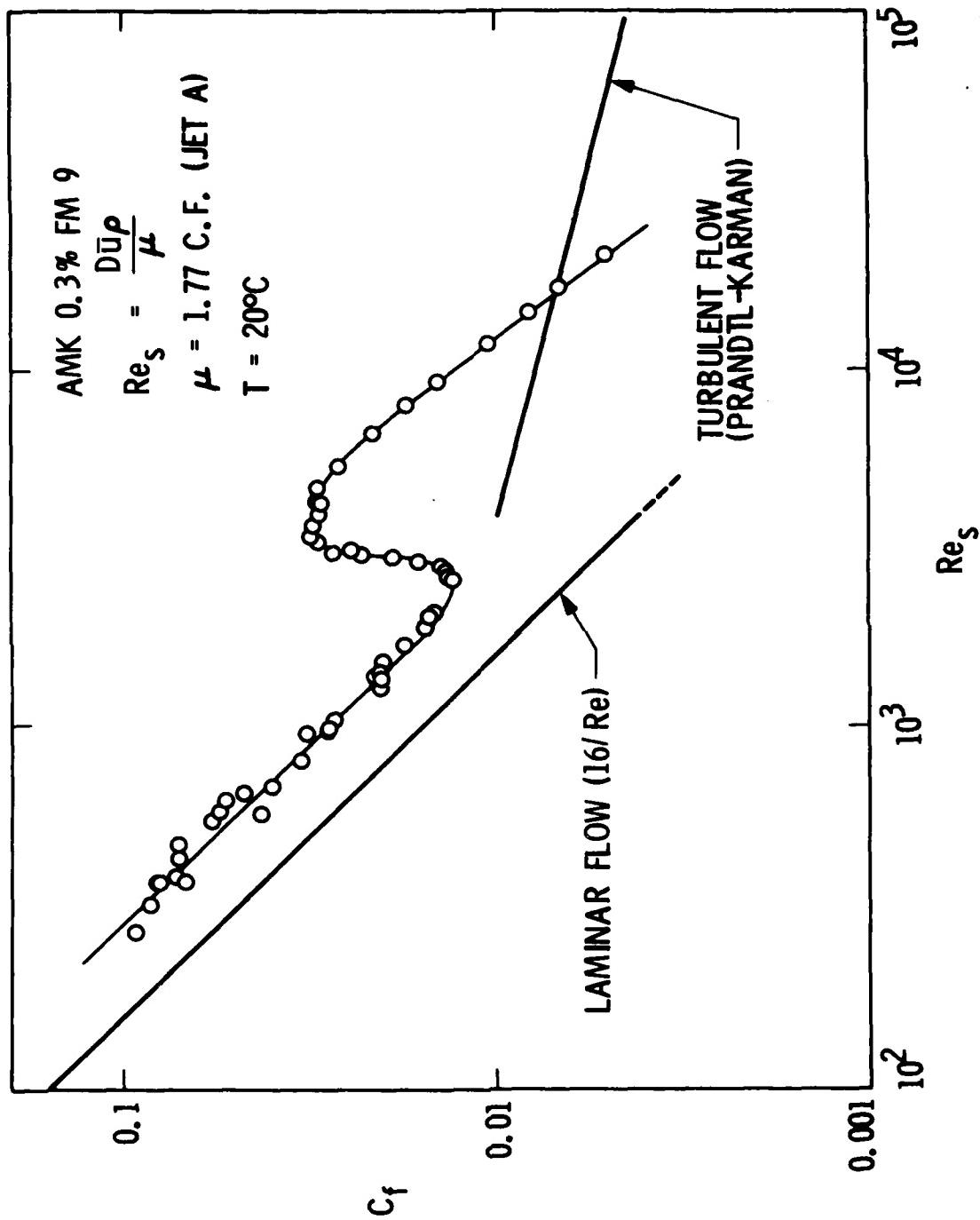
FIGURE 8-7. SKIN FRICTION VERSUS REYNOLDS NUMBER
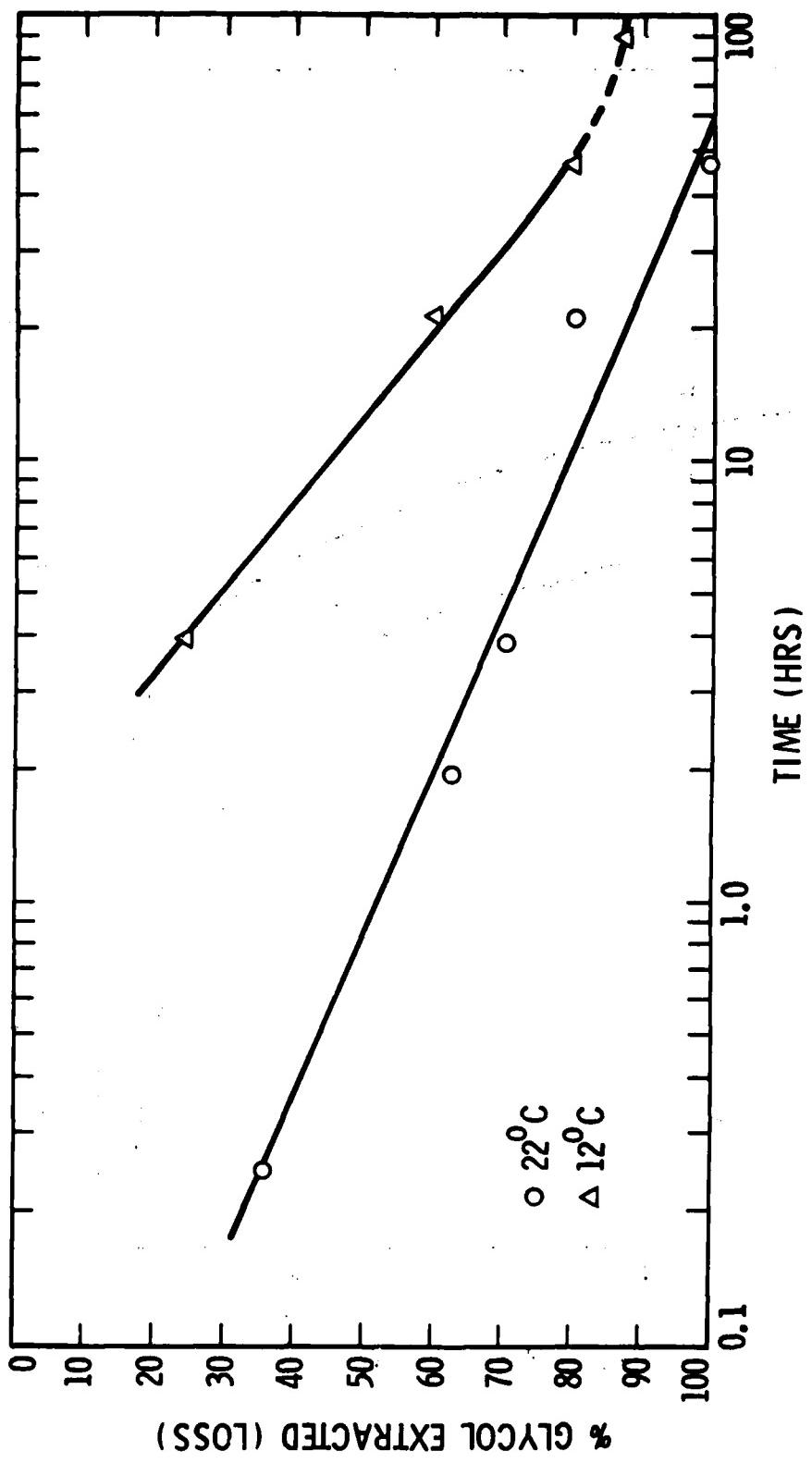
FIGURE 8-8. INFLUENCE OF LIQUID WATER ON ANTIMISTING FUELS
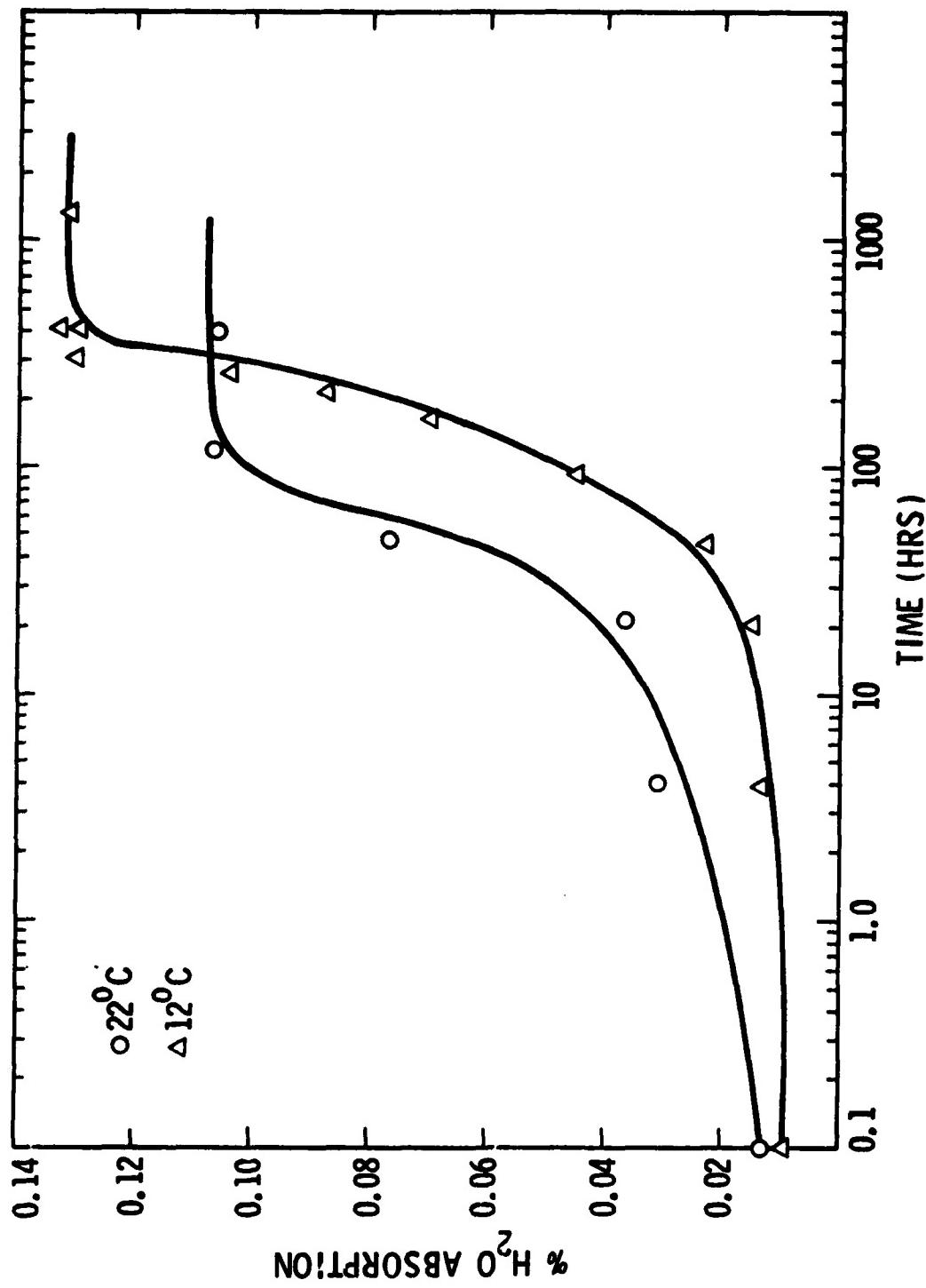
FIGURE 8-9.   UPTAKE OF WATER IN AMK

FUEL ATOMIZATION

OCCURS DURING BREAKUP OF FUEL FROM RUPTURED TANKS. DOMINATED
BY INERTIAL FORCES, VISCOUS FORCES, VISCOELASTIC, AND DYNAMIC
SURFACE TENSION

DROPLET EVAPORATION

MASS DIFFUSION DURING DROPLET DECELERATION DUE TO CONCENTRATION
GRADIENT OF VAPOR

MASS TRANSFER DUE TO TURBULENT HEAT TRANSFER FROM HEAT SOURCES
PRESENT IN A CRASH

COMBUSTION

DEPENDS ON LOCAL MEAN FUEL VAPOR/AIR RATIO, LOCAL TEMPERATURES,
AND ON TURBULENT MIXING

FIGURE 8-10.   FLUID DYNAMICS MECHANISMS THAT AFFECT FLAMMABILITY OF ANTIMISTING FUELS DURING A PLANE CRASH
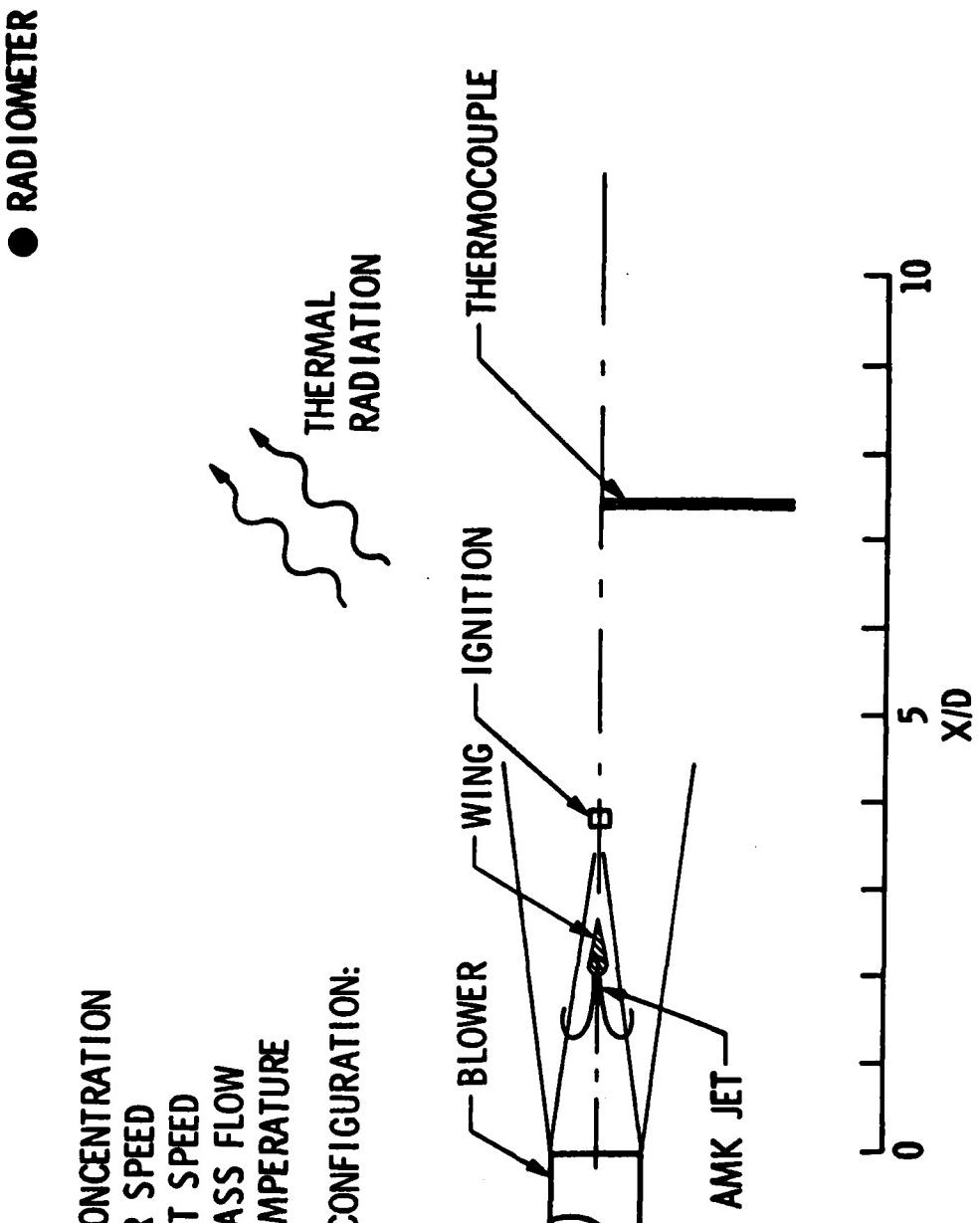
FIGURE 8-11. PARAMETRIC STUDY OF AMK FLAMMABILITY

FIGURE 8-12. IGNITION OF JET-A IN MINI WING-SHEAR FACILITY

FIGURE 8-13. IGNITION OF AMK IN MINI WING-SHEAR FACILITY WITH SAME FLOW CONDITIONS AS IN FIGURE 8-12
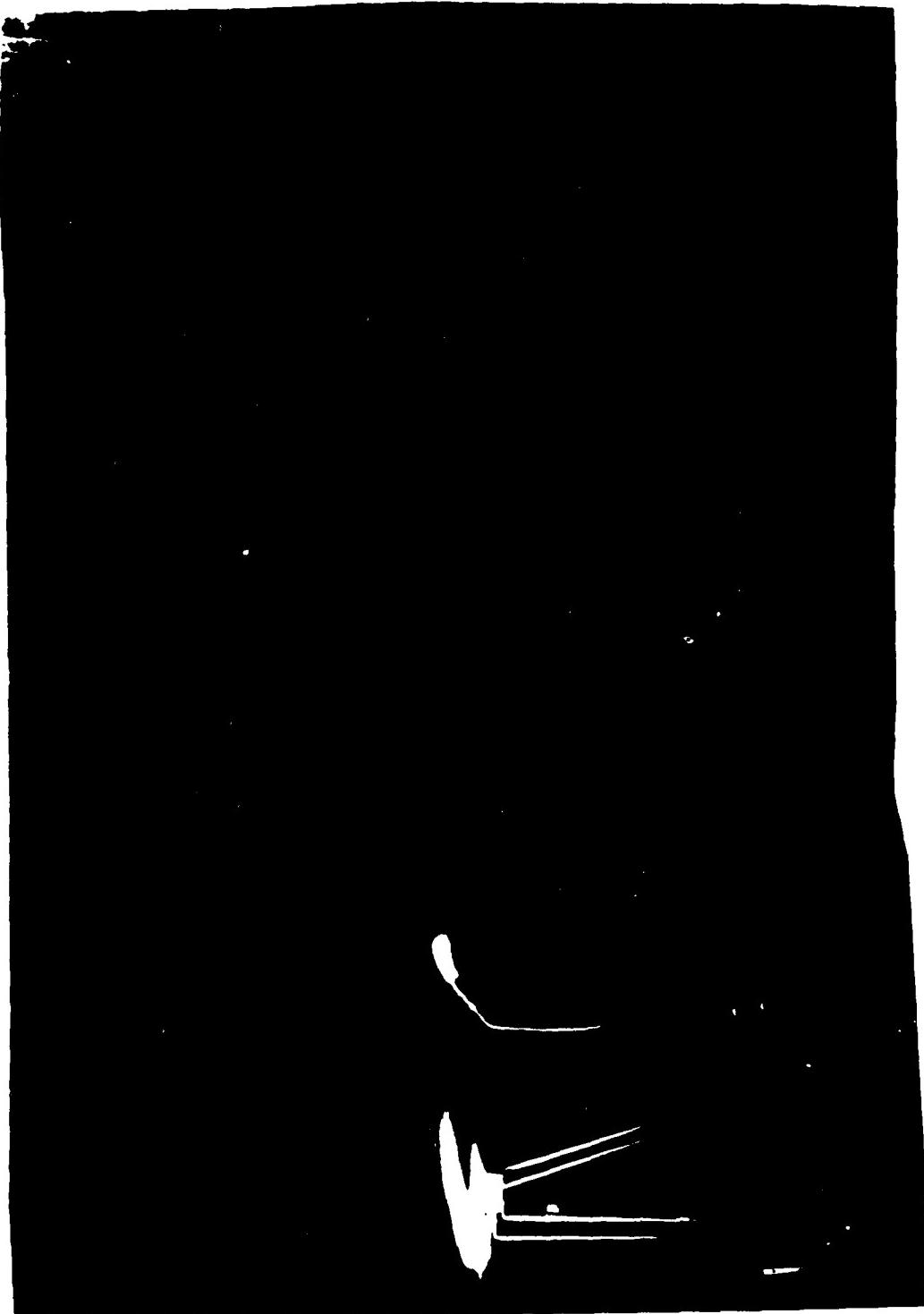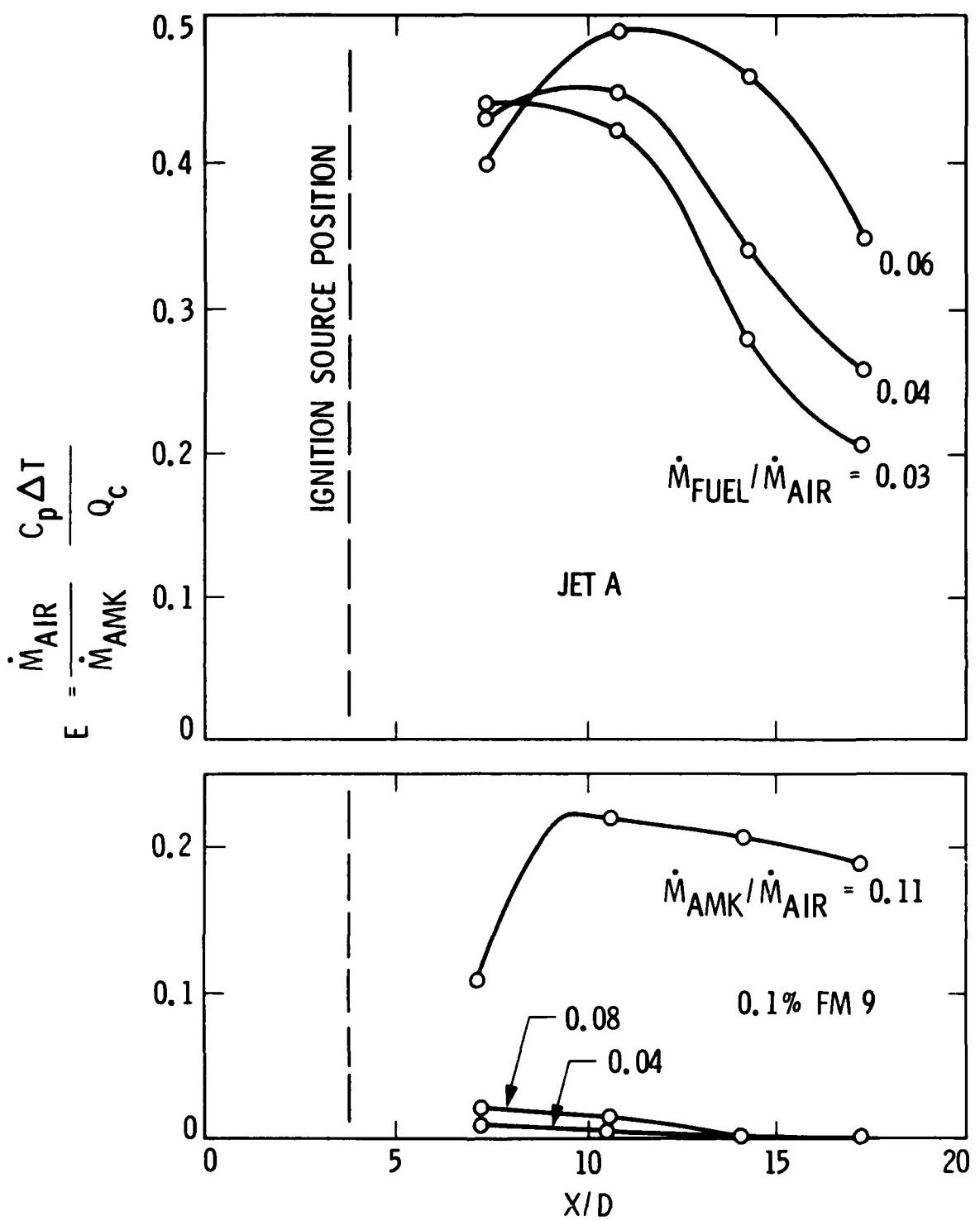
FIGURE 8-14.   TEMPERATURE DISTRIBUTION
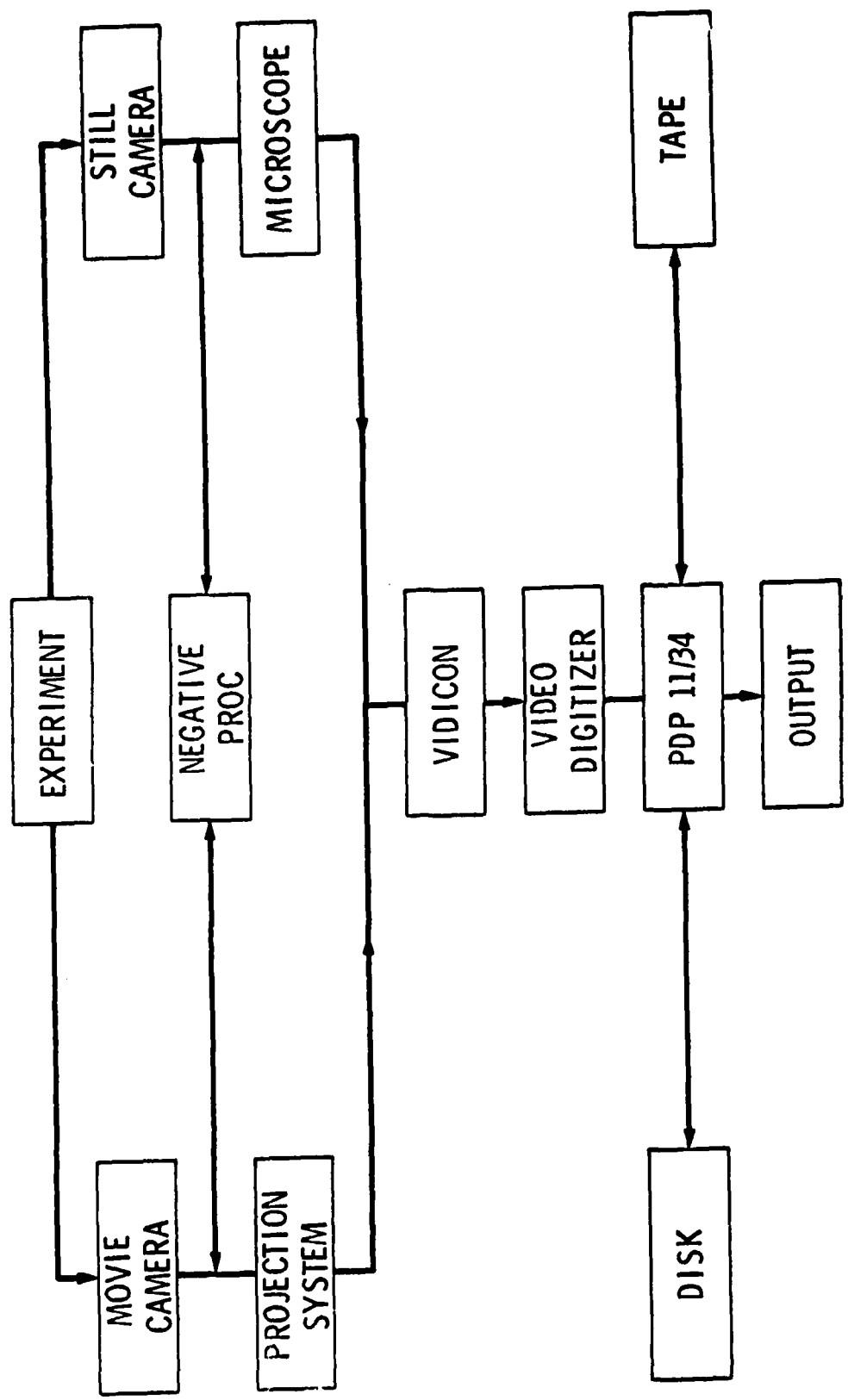
FIGURE 8-15. DIGITAL VIDEO SYSTEM FOR DROPLET IMAGING AND ANALYSIS

FIGURE 8-16.   ANTIMISTING FUEL BREAKUP IMAGES (ORIGINAL DATA)

FM-9 (0.3% BY WEIGHT)
VELOCITY = 70 METERS/SECOND
PASS CONDITION
THRESHOLD 160

FM-9 (0.2% BY WEIGHT)
VELOCITY = 70 METERS/SECOND
FAIL CONDITION
THRESHOLD 160
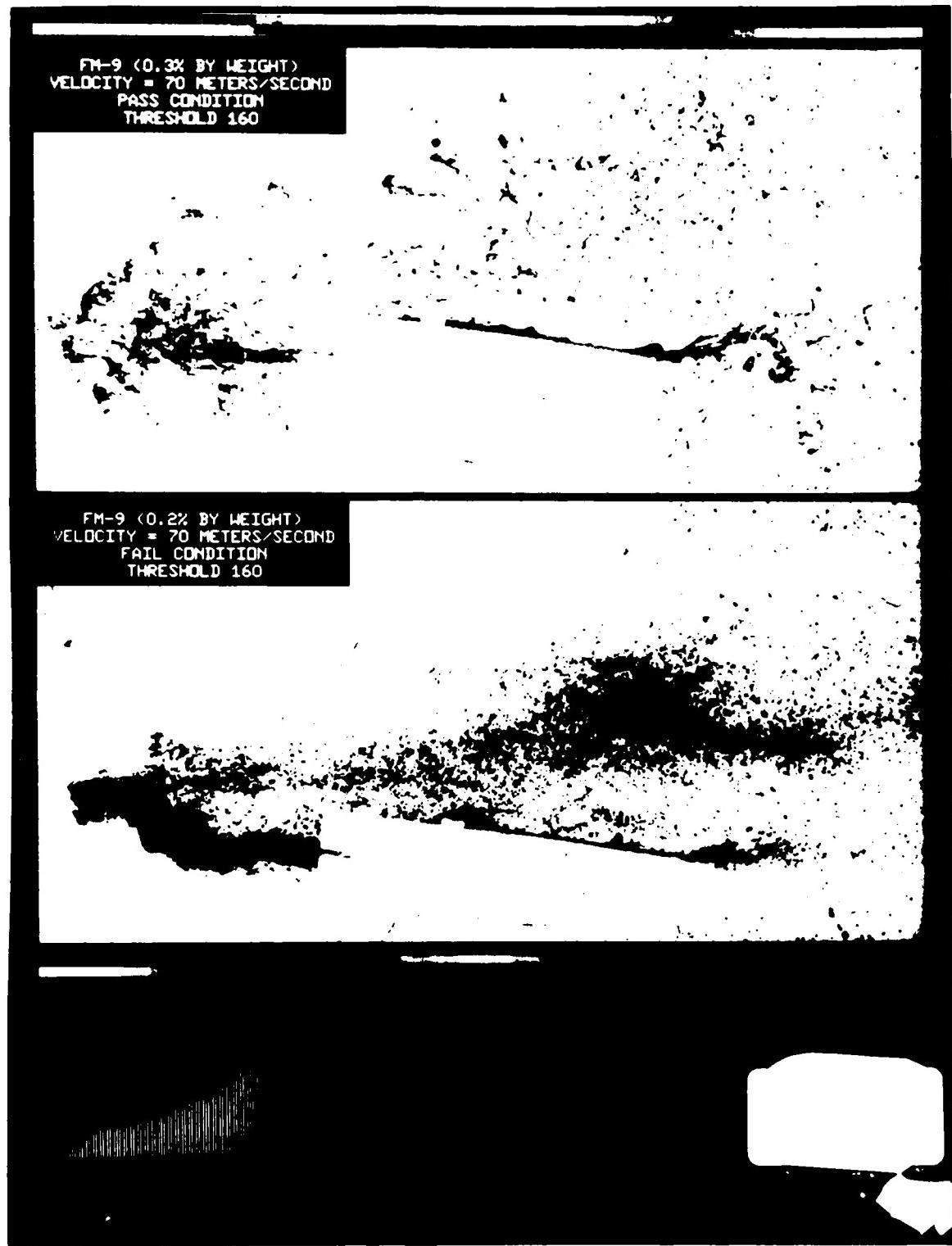
FIGURE 8-17. ANTIMISTING FUEL BREAKUP IMAGES (THRESHOLD 160)
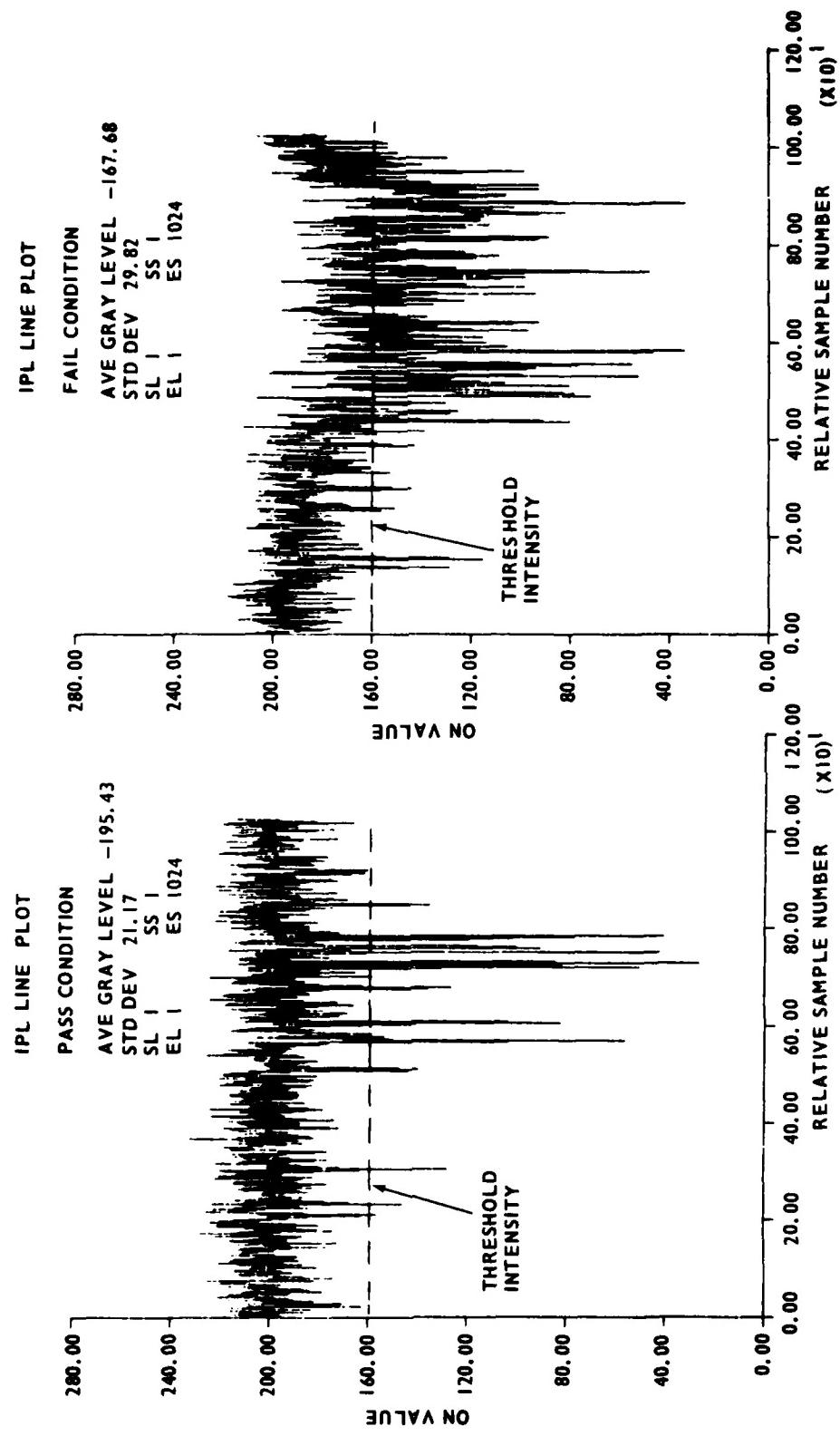
FIGURE 8-18.   PARTICLE DETECTION SYSTEM FOR IMAGE PROCESSING TECHNIQUE

PARTICLE GRADIENT ENHANCEMENT COLOR DENSITY SLICING

SUBSECTION OF PASS CONDITION

SUBSECTION OF FAIL CONDITION

FIGURE 8-19.   IMAGE ENHANCEMENT TECHNIQUE

8-28

Questions and answers following "Fundamental Studies of Antimisting Fuel"

Discussions:

Mr. Fiorentino: Pratt and Whitney Aircraft. On one of your slides, you had a plot that showed filter ratio as a function of water and on the bottom of the same slide you had a plot of volume flow versus water. Can I assume that volume flow versus water was done at constant pressure?

Mr. Sarohia: That is a standard ICI cup test.

Mr. Fiorentino: Were your points taken with the same filter or did you change filters after each measurement?

Mr. Sarohia: A new filter was used each time.

Mr. Fiorentino: Were there any signs of precipitation or gellation in the tests when the curve started to go up with the additional water?

Mr. Yavrouian: Jet Propulsion Laboratory. First, the curve goes down, then goes up. Everytime the filter test was run, two or three millimeters of gel buildup formed on the other side of the filter which does not increase if you keep adding more and more.

Mr. Sarohia: Actually, we have the feeling that water may be reducing a little bit of the gel formation.

Mr. Lampton: Serk Heat Transfer, England. We've seen how the viscosity of the fluid changes. Does the specific heat and the thermal conductivity change?

Mr. Sarohia: I think Tony has looked into that effect. Maybe you can ask him We have not investigated that.

DEGRADATION AND CHARACTERIZATION OF ANTIMISTING KEROSENE (AMK)

BY

R. J. Mannheimer, Ph.D

INTRODUCTION.

Antimisting kerosene (AMK) fuel contains a high molecular weight polymer (FM-9) that resists the formation of small droplets and has been shown to improve fire safety in simulated tests of ground crash conditions; however, poor fuel filtration and atomization characteristics preclude its use in aircraft turbine engines and fuel systems until acceptable means of restoring these essential fuel properties can be developed.

While both shear and elongational effects can contribute to polymer degradation, it is expected that elongational flows will be more destructive than shear flows. Some insight for this expectation can be provided by considering the differences between these two types of flows (figure 9-1). The familiar shear flow that is commonly produced in a long capillary tube is characterized by a velocity gradient that is normal to the direction of flow. As the dilute polymer solution flows through the capillary, polymer molecules tend to be stretched along the principal axis of stress. However, shear flows are rotational, and polymer molecules cannot stay oriented in the stress field; consequently, very little polymer deformation occurs with a low viscosity solvent even at high rates of shear. Elongational flows occur in many practical situations, such as in the entrance region to a capillary tube, in flow through an orifice, and porous media. In all of these examples, the velocity gradient is in the direction of flow. Since this type of flow is irrotational, a polymer molecule would be expected to stay oriented in the stress field longer; therefore, large polymer deformations should occur.

This work was performed at Southwest Research Institute, Mobile Energy Division, San Antonio, Texas, under FAA Contract DOT-FA 79WA-4310.

Because of the presence of solid boundaries, most flows are a combination of both shear and elongation; however, by an appropriate choice of geometry, one type of flow can be made to dominate. For example, laminar flow in a long capillary tube is primarily a shear flow except for the entrance region. On the other hand, in an orifice or a very short tube (L/D<<1) or for a tube filled with beads, the flow is predominately elongational.

Since elongational flow is expected to be more effective in producing polymer degradation than shear flow, the primary objective of this work is to determine the effect of the sudden acceleration produced by flow into the pores of metal screens or tubes packed with beads on the mist ignition and filtration properties of AMK. However, relatively few standard tests have been found to be useful in measuring the performance characteristics of AMK; therefore, a second but equally important part of this work is the development of test methods that relate to mist flammability and rheological properties of AMK.

POLYMER DEGRADATION EXPERIMENTS.

Polymer degradation xxperiments were conducted by displacing AMK from a large bore (12.7 cm) hydraulic cylinder. Before each run, approximately 6 liters of AMK

were charged to the rod side of the cylinder. A high pressure variable flow pump forced hydraulic fluid into the piston side of the cylinder, thus displacing AMK and forcing it to flow through the metal screens or packed tubes. The volumetric flow rate (Q) was the independent variable and was generally increased from a low value to the highest value (this was limited either by the maximum pressure of 4000 psi or by the maximum flow rate of 5 gal/min) and then back to an intermediate flow rate. This procedure was used to help detect hysteresis effects that might occur due to filter plugging. The pressure drop (P) was measured with a gauge and transducer, with the output of the latter recorded as a function of flow time. Since the pressure drop is a measure of specific degrader power, it has been expressed in terms of kWs/l instead of psi (1.0 psi= 0.0069kWs/l). A large-scale degrader that is more appropriate for aircraft applications and that utilizes a fuel pump from a TF-30 engine is currently being evaluated. The flow curves for AMK in tubes packed with 840-micrometer glass beads (figure 9-2) were almost identical to those of jet A and are representative of the high R_e flow regime in which the pressure drop increases with the superficial velocity in a nonlinear manner. At a given velocity, a higher degree of degradation (lower viscosity ratio) (The use of the viscosity ratio as a measure of polymer degradation is based on the relation of polymer size or molecular weight to intrensic viscosity.) can be produced by increasing the tube length. On the other hand, the increased degradation in the longer tubes is counterblanced by the requirement of a higher specific degrader power (figure 9-3). The relative effectiveness of packed tubes and screens are compared in figure 9-4. These results suggested that a simple orifice, such as a partially opened needle valve, could degrade AMK. Recent experiments substantiate that a needle valve is a very effective means of producing polymer degradation. In addition, the needle valve has two advantages over the use of screens or packed tubes, i.e., the ability to accommodate different flow rates at constant specific power and less likelihood of plugging due to dirt or other fuel contaminants.

MIST IGNITION EXPERIMENTS.

A spinning disc atomizer has been used to measure the resistance of AMK to form an ignitable fuel mist (figure 9-5). Four radially spaced 2-mm ID holes are provided as fuel passageways. Fuel flows into the central cavity in the disc head, and a oxy-acetylene ignition source is approximately 10 cm from the edge of the disc. As the rotational speed of the disc is increased, the fuel contacts the air at a higher relative velocity. Eventually, a velocity is reached at which ignition and flame propagation begins to occur. A radio meter is used to measure the effect of disc speed on flame propagation in the fuel mist. It is important to keep in mind that, with the spinning disc atomizer, the tengential component of velocity of the fuel is much higher than the radial component of velocity. Consequently, the spinning disc atomizer would be expected to produce significantly different results than a conventional pressurized atomizer. In particular, the velocity of the fuel relative to the surface of the fuel passage is relatively low, and this should minimize any mechanical degradation from occurring before the AMK contacts the air.

Mist flammability data for standard AMK (0.3 percent FM-9 + carrier fluid in jet A kerosene) degraded at different power levels and with different size beads are presented in figure 9-6. Below a velocity of 72 m/s, flame propagation of undegraded AMK is negligible compared to jet A. However, at higher velocities, flame propagation increases with disc velocity. It is important to note that this critical disc velocity is close to the pass/marginal air velocity for AMK made with

carrier fluid in fuel spillage tests conducted at FAA Technical Center. At low degrader power (3 to 4 kWs/l), the critical disc velocity is only slightly lower than undegraded AMK; however, at 15 kWs/l and higher, the mist flammability of AMK is indistinguishable from jet A.

Experiments were also conducted to determine the effect of the carrier fluid on mist ignition resistance and specific degrader power required to eliminate mist ignition resistance (figure 9-7). The critical velocity of undegraded AMK without carrier fluid is 15 to 20 m/s lower than standard AMK. This finding appears to be substantiated by large-scale flammability tests. However, a much higher power level is required before any significant reduction in the critical velocity can be detected. For example, at a power level of 3 to 4 kWs/l, the critical velocity of AMK with carrier fluid was reduced from 73 to between 48 to 52 m/s. At power levels up to 8 kWs/l, the critical velocity of AMK without carrier fluid remained essentially unchanged. Furthermore, at a power level of 15 kWs/l or greater, the mist flammability of AMK with carrier fluid was indistinguishable from jet A; however, the AMK without carrier fluid can be attributed to the fact that the FM-9 polymer is in a much tighter coil without the solubilizing effect of the carrier fluid and is, therefore, more difficult to degrade.

FILTRATION EXPERIMENTS.

At the beginning of this program, it was agreed by the U.S./UK Technical Committee that a standardized filtration test would be the primary measure of intentional degradation. Basically, this test is a viscometer in which a specific volume (96 ml) of fuel flows between two timing marks on a vertically mounted glass tube (2.5 cm ID). A 16- to 18-micrometer Dutch weave screen is attached to the bottom of the tube, and the flow time for AMK, relative to jet A is reported as the For undegraded AMK at 25° C, this ratio is generally between 40 and 50; however, degradation can reduce this ratio to close to 1.0.

The effect of bead size on polymer degradation as measured by the filtration ratio is shown in figure 9-8. The lowest filtration ratio for fuel degraded with the 840-micrometer beads was 2.0. Although filtration ratios as low as 1.0, have been reported from UK (AMK after it has had been processed by the UK degrader), these low values are partly due to the fact that the fuel is at an elevated temperature (50° to 60° C above ambient). For example, results with the latest model UK degrader (D70) indicate that the filtration ratio of AMK processed at 75 kWs/l was approximately 1.0 at elevated temperatures and increased to approximately 2.0 after the fuel was cooled to ambient.

Increasing tube length generally lowe. the ˙perficial velocity required to produce the same filtration ratio; howe..r, as with the viscosity ratio, a longer tube requires a higher specific degrader power.

Similar experiments were conducted with smaller glass beads (420 micrometer) and two different length tubes. Except for one important difference, the results of these experiments are in good agreement with those obtained with the larger beads (840 micrometer). This difference suggests that degradation with small beads is more efficient. For example, the results of tube length on the specific degrader power required to reduce the viscosity ratio to a particular value was almost identical for both size beads. However, the effect of bead size on filtration ratio was significant. In particular, the specific degrader power required to produce a filtraton ratio of 2.0 was approximately twice as high for the larger

9-3

beads (24 kWs/l compared to 12.5 kWs/l). However, as was seen earlier in figure 9-4, there was no significant effect of bead size on the viscosity ratio. The significance of these differences will become evident after we take a closer look at the standard filtration ratio test.

The laminar flow of dilute polymer solutions through porous media is often characterized by two distinctly different flow regimes. Below a critical strain rate, the flow resistance is determined by the shear viscosity; however, at higher rates of strain, the flow resistance increases dramatically and can become orders of magnitude higher than the shear viscosity. This high-resistance flow regime is a viscoelastic associated with the elgonational flow field that is characteristic of porous media. Because of the gel-forming tendency of the FM-9 polymer, it is difficult to differentiate between this inherent viscoelasticity and filter plugging with the standard filtration test. Consequently, more detailed experiments were conducted by maintaining a fixed gas pressure over a fluid reservoir and collecting a quantity of filtrate over a timed interval. This procedure is similar to the standard test, but it has several important advantages. For example, by measuring the flow rate or velocity at different pressures, more information can be obtained on the rheological behavior of AMK. Also, by making measurements at increasing and decreasing pressures, effects of filter plugging can be easily detected.

The results in figure 9-9 demonstrate the flow characteristics of Newtonian liquids, in this case jet A and diesel fuel. Measurements were taken at increasing and decreasing pressures to detect filter plugging. It is interesting to note that the superficial velocity for jet A at a pressure head of 20 cm is approximately 4 cm/s. This is close to the average superficial velocity of 4.4 cm/s for jet A in the standard filtration test. (While the average superficial velocity (V) is not reported in the standard filtration test, it can be calculated from the fuel volume (96 ml) and screen area (4.5 cm)^2, i.e., V = 21.3/t, where t is the flow time in seconds.) This illustrates the similarity in flow conditions between the standard filtration test and this experiment.

The linear flow characteristics shown in figure 9-9 are representative of the laminar flow regime in which the Darcy Equation is valid:

$$V = \frac{K \Delta P}{\mu L} \qquad (1)$$

where V = Q/A is the superficial velocity, ΔP is the pressure drop, L is the filter thickness, μ is the absolute (shear) viscosity, and K is the permeability.

More general relationships for non-Newtonian behavior have been derived, but for now, this simple relation will be used. Since the permeability is a function of several factors such as pore size, pore shape, and porosity or void fraction, the following comments will refer to a specific filter configuration, i.e., 16- to 18-micrometer, stainless steel, Dutch weave. In this case, the Darcy Equation predicts that the velocity ratio of jet A relative to diesel fuel (i.e., the filtration ratio) will be 3.8 cP/1.5 cP = 2.53. This is very close to the measured value shown in figure 9-9. Thus, while there is a large difference between the filtration ratio (40 to 50) and viscosity ratio (1.75 to 1.75) for undegraded AMK, the Darcy Equation predicts that these two measurements will have a common asymptote (i.e., FR VR) for highly degraded AMK. Furthermore, this result demonstrates that the standard filtration test is basically a viscometer. Filtration

measurements for two highly degraded samples of AMK substantiate this prediction for a 16- to 18-micrometer screen but not for paper filters:

Filtration Ratio

Viscosity Ratio	16- to 18- Metal	20- Paper	10- Paper
1.17*	1.1 (1.2)	8.6 (13.6)	27 (32)
1.22**	1.3 (1.2)	3.4 (3.2)	33 (33)

* FM-9 with carrier fluid in jet A, 25kWs81 - SwRI degrader
** FM-9 with carrier fluid in jet A-1, 100 kWs81 - RAE degrader

If these samples were fully degraded, the filtration ratio should be the same value as the viscosity ratio regardless of the filter material. Consequently, the increasing filter ratio with decreasing filter size indicates that the standard filtration test, which specifies a 16- to 18-micrometer metal screen, overestimates the level of polymer degradation. This sensitivity of paper filters to plugging by partially degraded AMK is probably due to at least three factors: (1) the pore size and shape distribution of a paper filter is broader than a metal filter; (2) the effective open area of a paper filter is less than a metal filter (this results in higher local velocities); and (3) a metal filter is only one pore deep, while a paper filter has an effective depth of several pores. This last factor is particularly important in that gel formation occurs after AMK flows through the first pore. While this results in the gel forming on the downstream side of a metal filter, gel forming inside a paper filter results in rapid plugging. In addition, it was suspected that part of the problem with the standard filtration ratio test was due to the very shcrt flow time (approximately 4 to 5 seconds) available for gel formation.

In order to test this hypothesis, filtration experiments were conducted with jet A and a highly degraded AMK sample (VR = 1.2, FR - 1.2) at different pressure gradients and for different flow times. This particular AMK sample was degraded by RAE at a power level of 100 kWs/l. The results of these experiments (figure 9-10) show no effect of flow time on the velocity of jet A over the range of 0.5 to 3.0 minutes. However, different results were observed for the degraded AMK, dependin] on the flow time. For a relatively short time of 30 seconds or less, the superficial velocity of the degraded AMK increased linearly with increasing pressure drops. For a flow time of 2 minutes, a critical velocity is evident at 3 cm/s, and at a flow time of 3 minutes, the critical velocity was close to 1 cm/s. The hysteresis loops for flow times above 2 minutes clearly indicate that the critical velocity is associated with gel formation and filter plugging.

This result confirmed that the filtration ratios in the standard test were low, due to the relatively short flow time (4-5 seconds) for this test. Consequently, experiments were conducted in which the flow time in the filtration ratio test was increased by decreasing the cross-sectional area of the filter. This was achieved by placing the filter paper or screen between two discs that had a hole in the center of the desired size. Data were obtained for areas from 5.0 cm^2 (standard filtration ratio test) down to 0.2 cm^2. The flow time was first measured for jet A and then AMK, and each filtration ratio was obtained with a fresh filter paper. Since the time for the flow of 96 ml of jet A increased inversely with the

filter area, the average velocity (V=Q/A) remained essentially constant at 4.5 cm/s. On the other hand, the velocity of degraded AMK samples generally decreased with increasing flow time or decreasing area.

The results shown in figure 9-11 were obtained with a degraded sample of AMK (FR= 1.4) and two different types of filter material (i.e., the standard 16- to 18- micrometer screen and 40-micrometer paper used in the JT8D main fuel filter). These results show that while the velocity of jet A is independent of the flow time or area, the velocity of degraded AMK decreases with increasing jet A flow time (i.e., decreasing area). While this phenomenon occurs with both metal screens and paper filters, it is evident that the limiting filtration velocity is reached sooner with the paper filter. These same results are presented in figure 9-12 in terms of filtration ratios instead of filtration velocities. One might conclude that the filtration ratio test could be improved by the use of paper filters instead of metal screens. However, data for two different samples of degraded AMK show that results depend on the filter area or flow time even with paper filters (figure 9-13). One sample was degraded by three passes through a JT8D fuel pump (3.5 kWs/l per pass, 1650 pounds per hour (pph) fuel flow, 7350 pph recirculated flow) and is characterized by a room temperature filtration ratio of 1.4 to 1.5 with a 16- to 18-micrometer screen. Since the filtration ratio with the 40-micrometer paper filter is almost an order of magnitude higher, it is evident that this sample is not highly degraded. As the filter area is reduced, the filtration ratio at first increases and then approaches a limiting value (47).

The second sample, which was degraded by a single pass through a needle valve (1326 pph, 24 kWs/l), is characterized by a filtration ratio of 1.2 with the standard 16- to 18- micrometer screen and by a filtration ratio of 1.5 for a 40-micrometer paper filter. This is almost an order of magnitude lower than the 3-pass sample. This low filtration ratio would suggest a very high degree of degradation. Unfortunately, when measurements were made with different filter areas, the filtration ratio increased, and eventually surpassed that of the 3-pass sample. More importantly, these results demonstrate that filtration ratios, as measured by the filtration apparatus that is currently in general use, can result in serious errors even if the metal screens are replaced by paper filters regarding degradation. While it is possible to obtain a better estimate of the filtration ratio by decreasing the area, this approach is very tedious.

The results of these experiments confirm that the flow time (4 to 5 seconds) in the standard filtration test is too short to detect gel formation with highly degraded AMK. Although, the previously described experiment is capable of detecting these effects, the time-dependent nature of this phenomenon suggested the need for a filtration test that more closely simulated flow conditions in an aircraft fuel delivery system, and in particular one that is able to measure flow resistance as a function of time.

In the pump filtration test, a gear pump (0-100RPM) and drive transmission are used to force fuel through a filter at different flow rates. The pressure drop across the filter is measured as a function of time by a transducer and strip chart recorder. For the following experiments, the flow time was held constant at 2 minutes. Experiments conducted with jet A (figure 9-14) showed no measurable increase in pressure over the 2-minute interval. Furthermore, the pressure drop increased linearly with increasing superficial velocity (which is characteristic of laminar flow of a Newtonian liquid), and there was no evidence of hysteresis when the velocity was decreased. It is also important to note that at a velocity

of 4 cm/s, the measured pressure drop was 20 psi. This is close to the average pressure drop that results in a velocity of 4 to 5 cm/s for jet A in the standard filtration test.

Significantly different experimental results (figure 9-14) were obtained with what should have been highly degraded AMK, as evidenced by the filtration ratio of 1.2 at 25° C. In this case, the pressure drop remained independent of time as long as the velocity was below 1 cm/s. It is more important to note that the value of the filtration ratio is equivalent to an average velocity in the standard filtration test of close to 4 cm/s. At higher velocities, the pressure drop increased linearly with time after a short induction time. The effect of increasing pressure with time is illustrated by the separation of the data points at a fixed velocity. The rate of pressure rise with time was significantly higher as the superficial velocity increased above 1 cm/s. While this effect appeared to be reversible in that the pressure drop was independent of time when the velocity was reduced below 1 cm/s, the hysteresis loop is definite evidence of filter plugging (i.e., P = 5 psi at V = 0.9 cm/s for V increasing and P = 100 cm at V - 0.9 cm/s for V decreasing).

The pump filtration test is currently being used to estimate the conditions for which AMK will flow through a filter like a Newtonian liquid. The critical velocity is determined by the highest velocity at which the pressure drop, across the filter, remains constant for 2 minutes.

The results in figure 9-15 show that two samples of degraded AMK that have close to the same filtration ratio have critical filtration velocities that are significantly different.

Because of the observed effect of a surfactant on the gel-forming characteristics of FM-9, pump filtration experiments were also conducted to determine the effect of a surfactant on the critical filtration velocity of undegraded AMK. The results in figure 9-16 show that the critical filtration velocity increases in direct proportion to the amount of surfactant added over the range of 0 to 0.5 by weight of per cent surfactant. At a concentration of 0.5 percent surfactant, undegraded AMK is able to flow through a paper filter at velocities equivalent to takeoff conditions (figure 9-16).

It is important to mention that while the surfactant obviously reduces gel formation and improves the filterability of AMK, it does not appear to adversely affect fire safety. This result makes it difficult to attribute the mist fire resistance of FM-9 to its gel-forming characteristics.

Preliminary experiments have been conducted with full-scale aircraft fuel filters. The results presented in figure 9-17 are for the flow of jet A and degraded AMK (21 kWs/l needle valve, 3000 pph) through a fuel filter assembly (i.e., filter and filter-holder) that has been used for the CF-6 engine. The data for jet A shows that the pressure drop across the filter assembly increases with flow rate in a nonlinear manner. This is indicative of a flow resistance that is due primarily to inertial effects or turbulence. The flow resistance of the filter itself to jet A was determined by subtracting the pressure drop through the filter assembly at a given flow rate without the filter from the pressure drop through the assembly with the filter. The almost linear increase in pressure drop with flow rate indicates that flow through the filter is laminar.

The results for the degraded AMK, which has only a slightly higher viscosity than jet A (i.e., 1.1 - 1.2 times higher than jet A) lie very close to the curve for jet A, even at flow rates in excess of those expected at takeoff (10,000 pph). Because of the relatively small amount of degraded AMK (40 gallons), it was necessary to recirculate the fuel through the filter with a small (1/3 hp) pump. While it is felt that this should have little or no effect on the already highly degraded AMK, these results should be considered tentative until larger quantities of AMK can be tested. However, it should be mentioned that attempts to flow undegraded AMK through this filter even at flow rates of as low as 2000 pph resulted in immediate filter plugging.
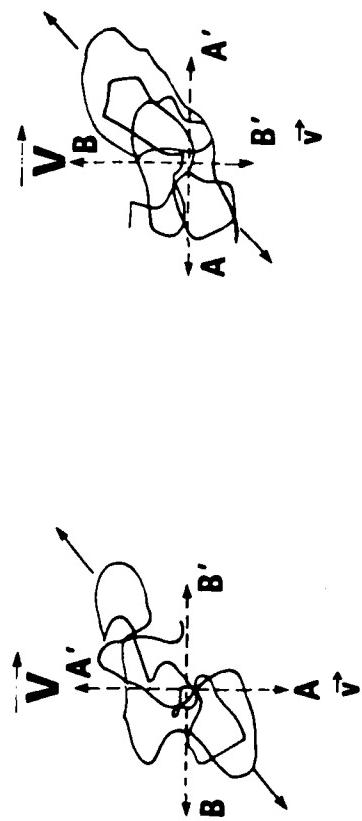
STEADY SHEAR FLOW $(\omega=1/2\dot{\gamma})$
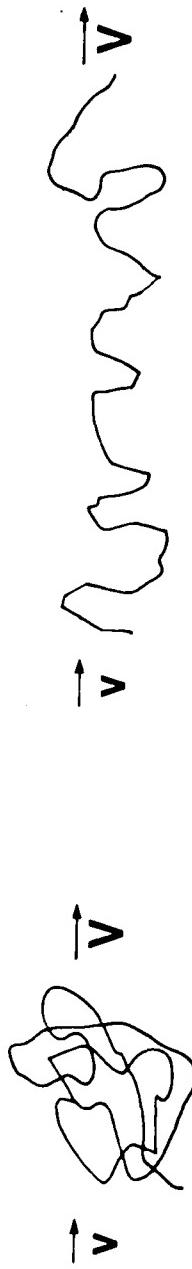
ACCELERATIVE (ELONGATIONAL) FLOW

FIGURE 9-1.   ILLUSTRATIONS OF STEADY SHEAR FLOW AND ACCELERATIVE FLOW

9-9
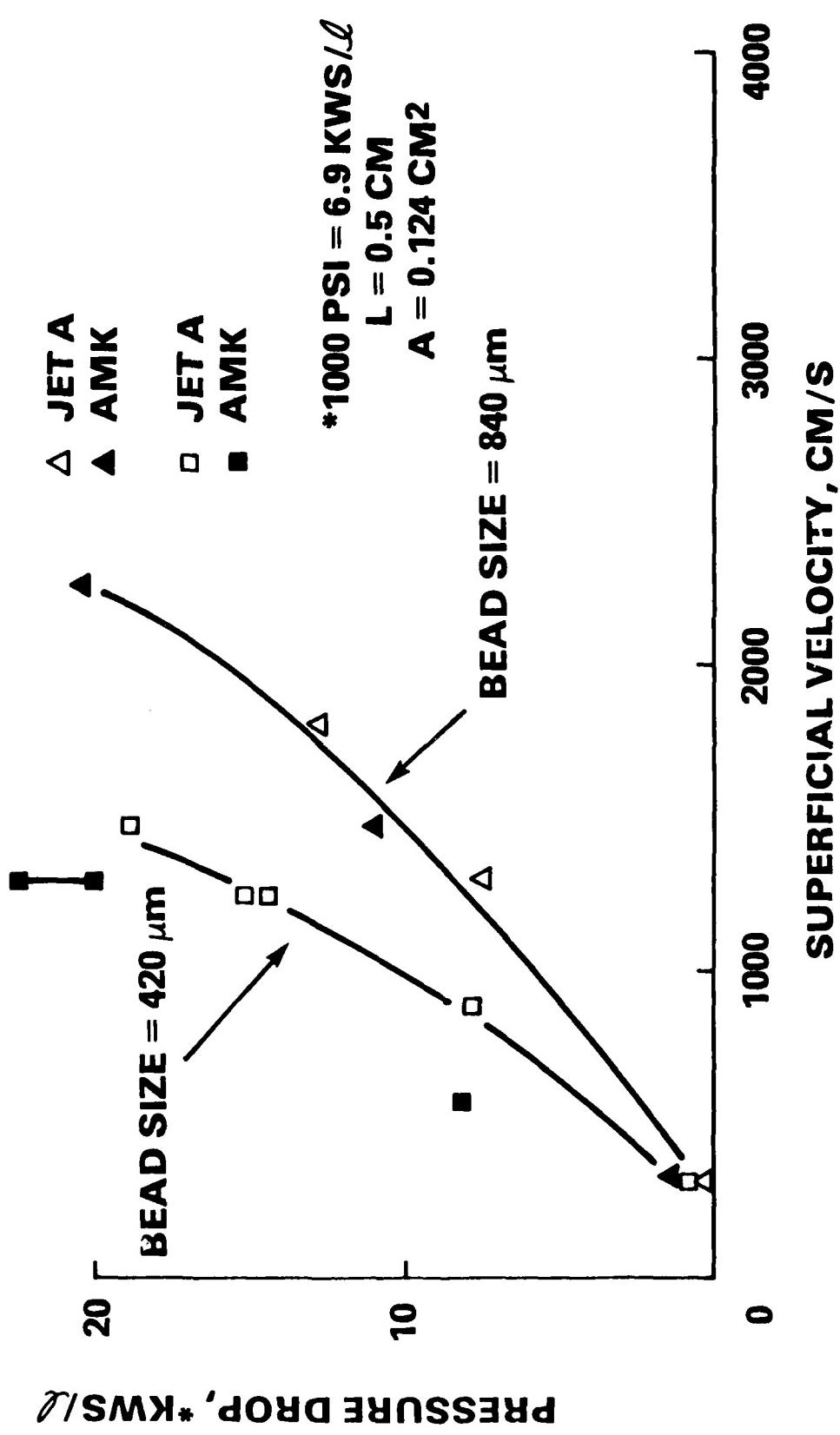
FIGURE 9-2.   FLOW OF AMK AND JET A THROUGH PACKED BED
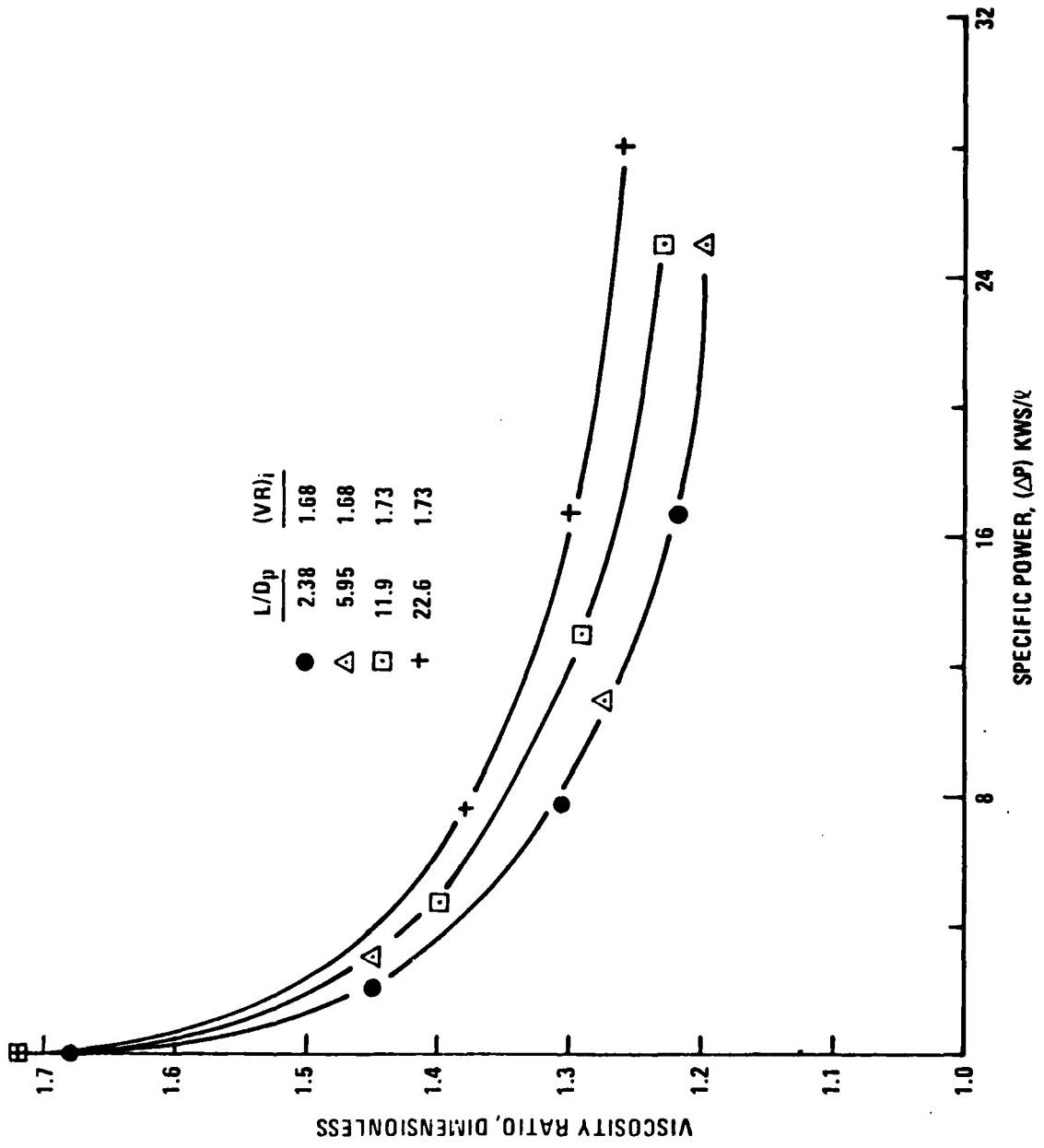
FIGURE 9-3.   EFFECT OF TUGE LENGTH (L/D$_p$) AND SPECIFIC POWER (ΔP) ON VISCOSITY RATIO (VR) (D_p = 840 µm, A = 0.124 cm^2)
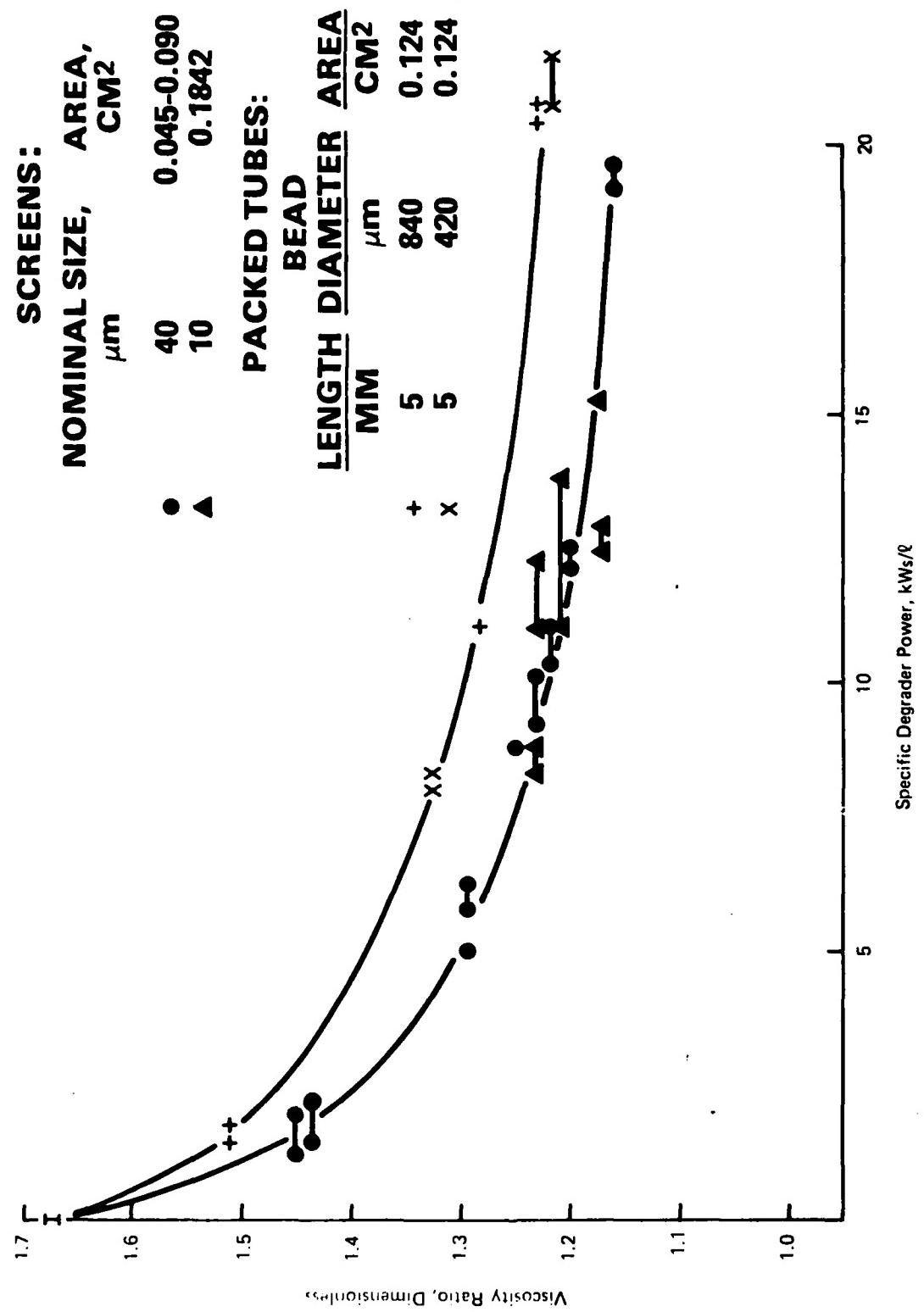
FIGURE 9-4. POWER REQUIREMENT FOR FLOW DEGRADATION OF AMK
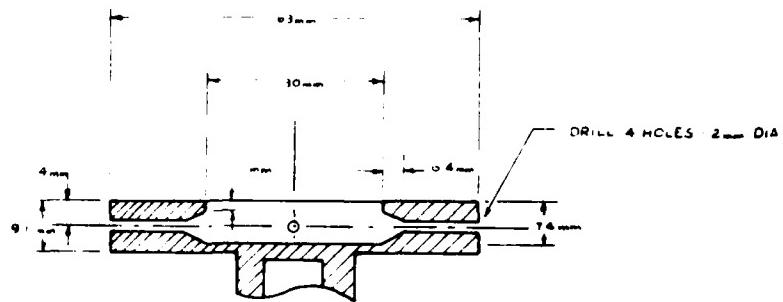
A) CROSS SECTION OF DISC

B) FUEL FLOWS INTO CAVITY

C) VELOCITY OF DISC PRODUCES IGNITABLE FUEL MIST.

FIGURE 9-5.   MIST IGNITION (SPINNING DISC) APPARATUS

9-13
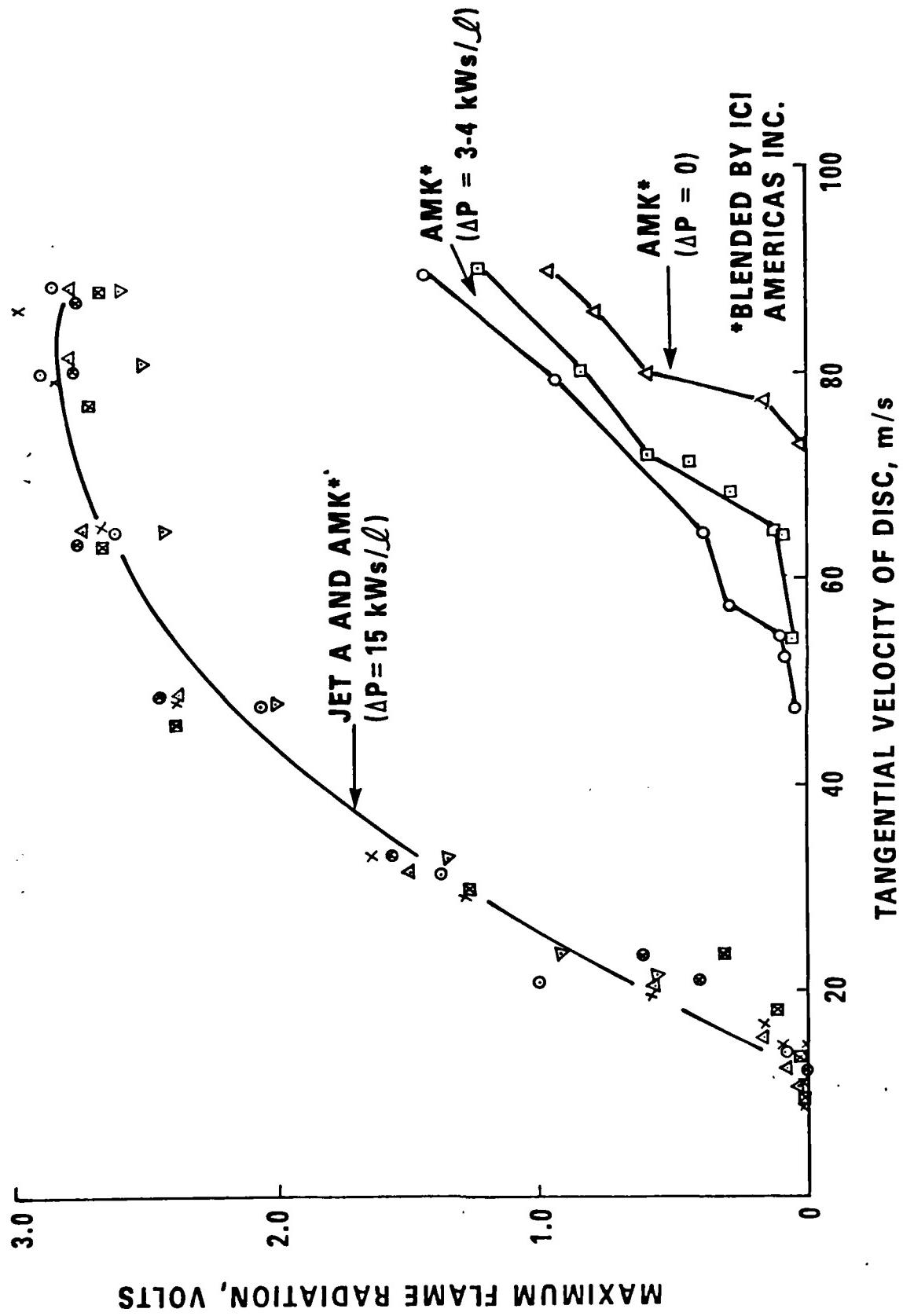
FIGURE 9-6. EFFECT OF DEGRADATION ON MIST FLAMMABILITY OF AMK
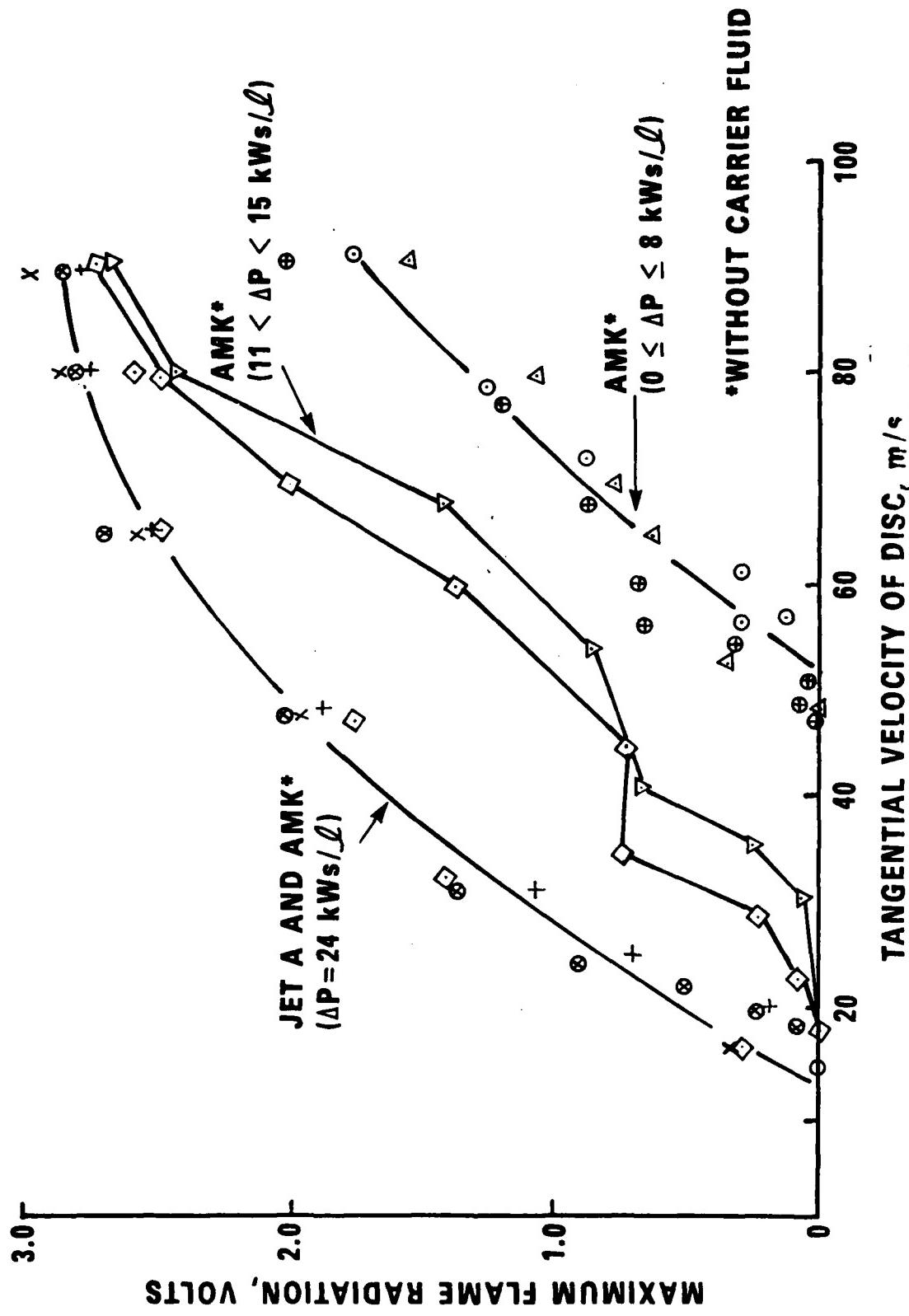
FIGURE 9-7.   EFFECT OF DEGRADATION ON MIST FLAMMABILITY OF AMK WITHOUT CARRIER FLUID
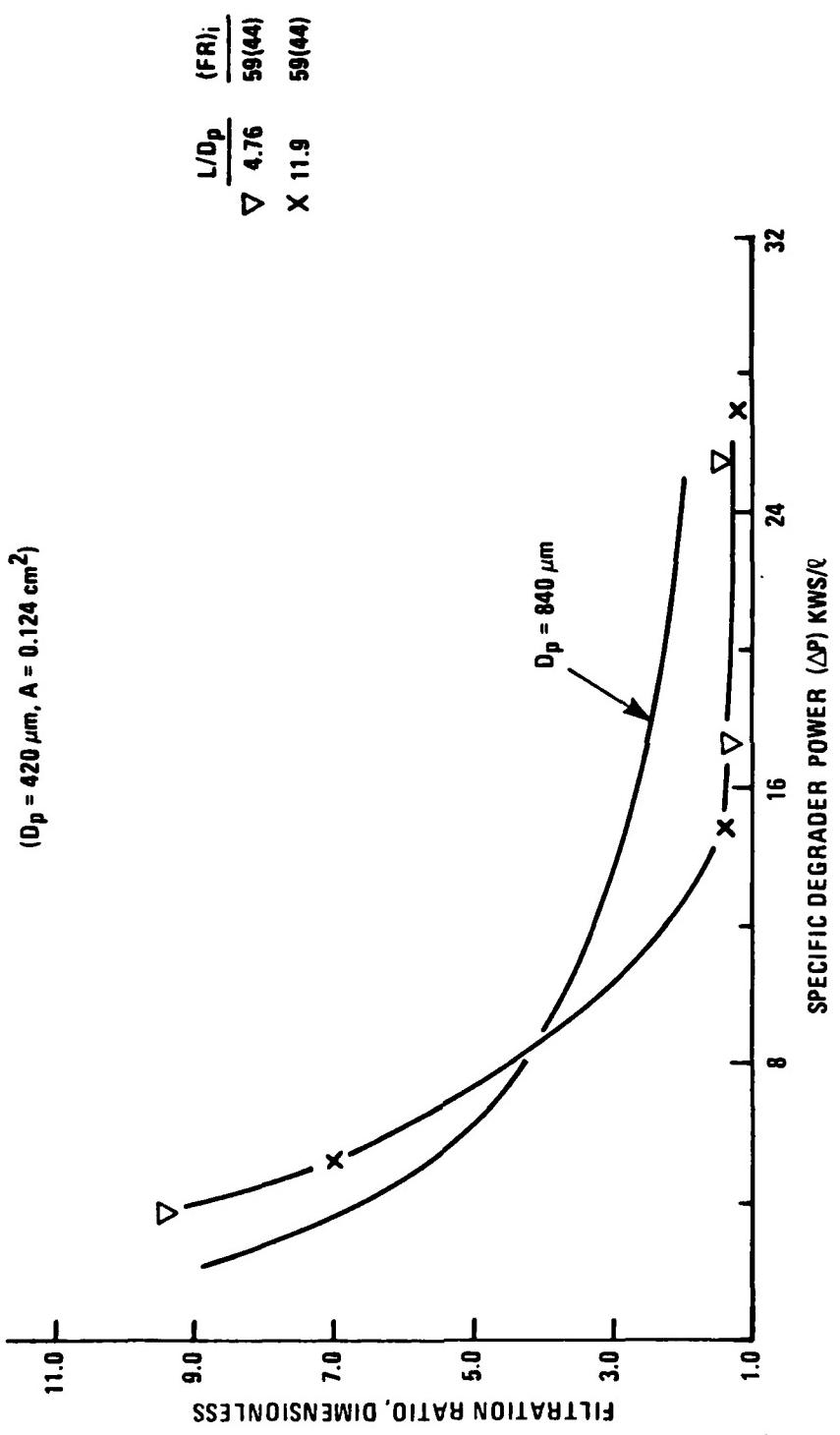
FIGURE 9-8. EFFECT OF TUBE LENGTH (L/D$_p$) AND SPECIFIC POWER (ΔP) ON FILTRATION RATIO (FR)

5.0

4.0

Superficial Velocity, cm/s

3.0

2.0

1.0

1.5 cp @ 25° C

Darcy Eq:
$$V = \frac{k\ \Delta P/L}{\mu}$$

3.8 cp @ 25° C

16-18 μm
Dutch Weave
A = 0.4 cm^2
● — Increasing ΔP
◉ — Decreasing ΔP

0   5   10   15   20   25
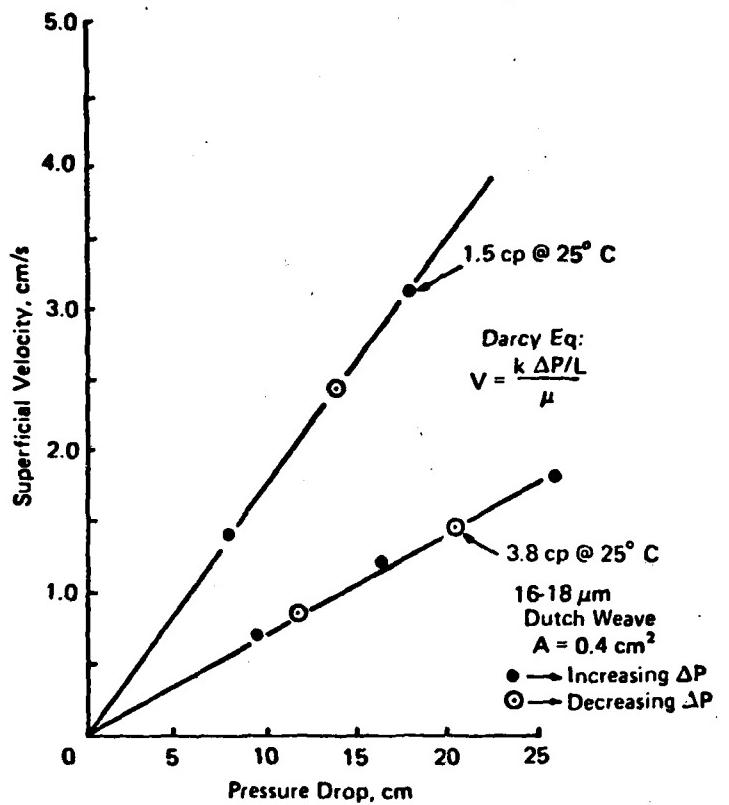
Pressure Drop, cm

FIGURE 9-9.   EFFECT OF PRESSURE DROP ON SUPERFICIAL VELOCITY
OF NEWTONIAN LIQUIDS THROUGH METAL FILTERS
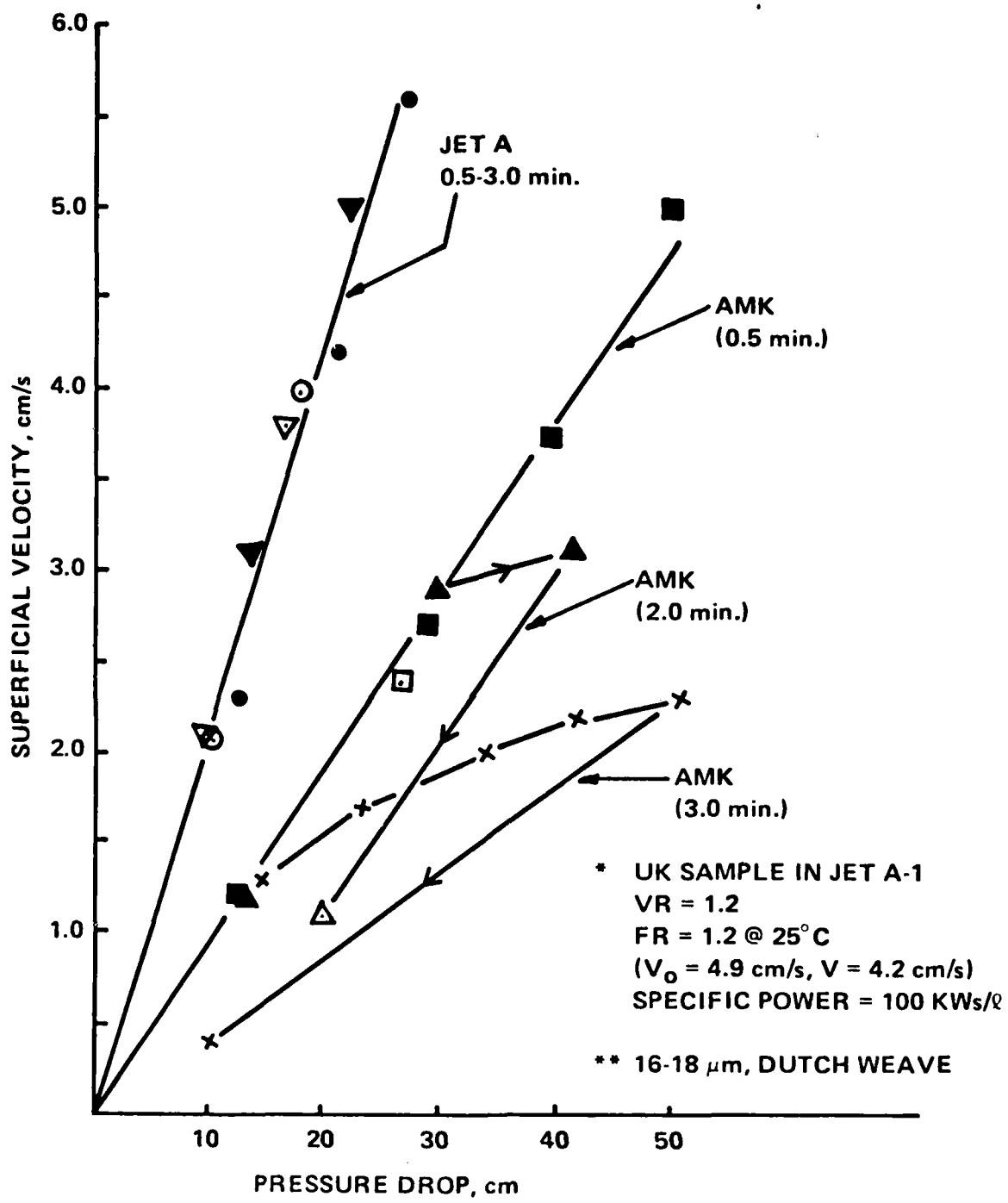
FIGURE 9-10. EFFECT OF PRESSURE DROP ON SUPERFICIAL VELOCITY
OF HIGHLY DEGRADED AMK* THROUGH METAL FILTERS**
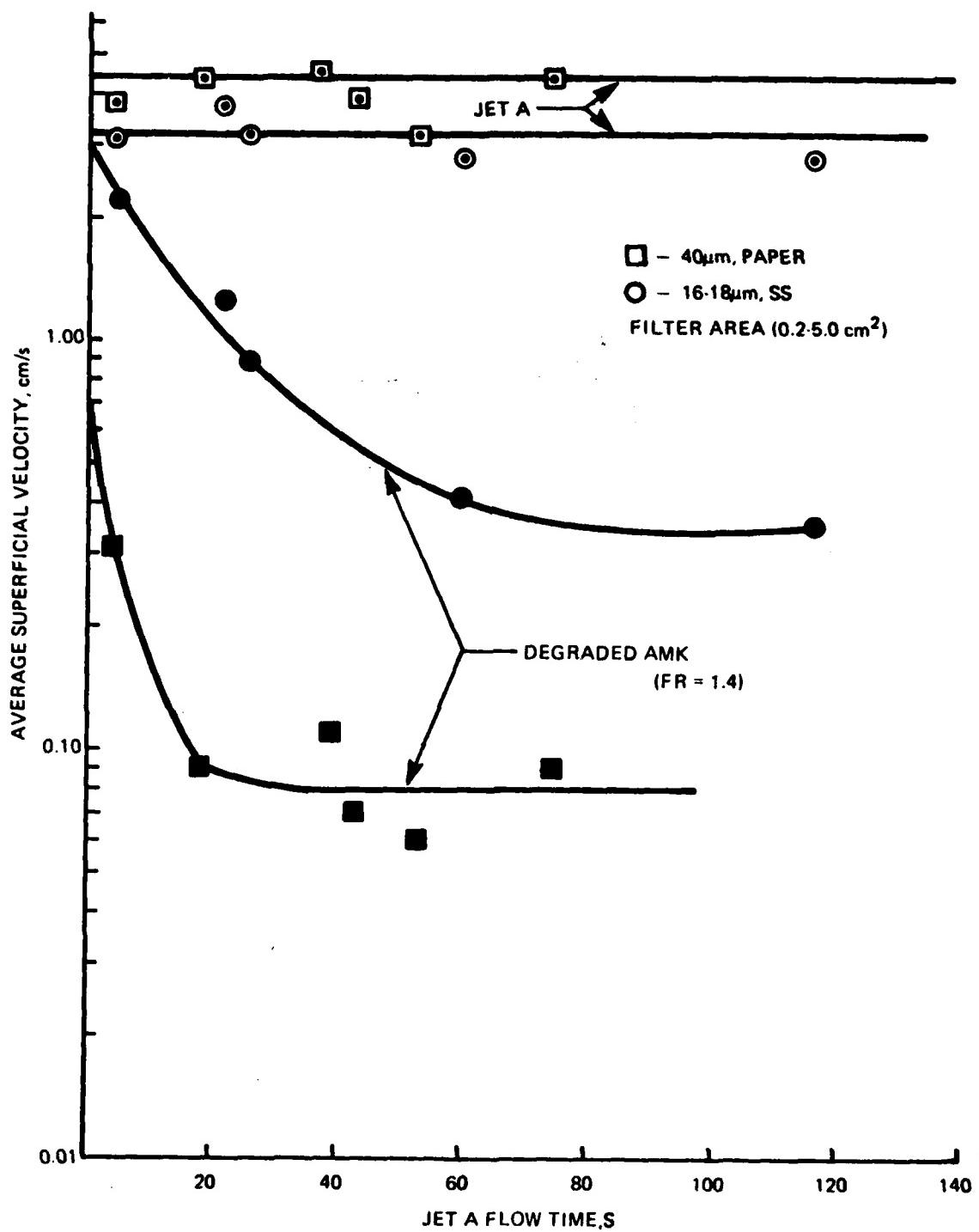
FIGURE 9-11.   EFFECT OF FLOW TIME (AREA) ON FILTRATION VELOCITY
OF DEGRADED AMK IN TWO DIFFERENT FILTERS
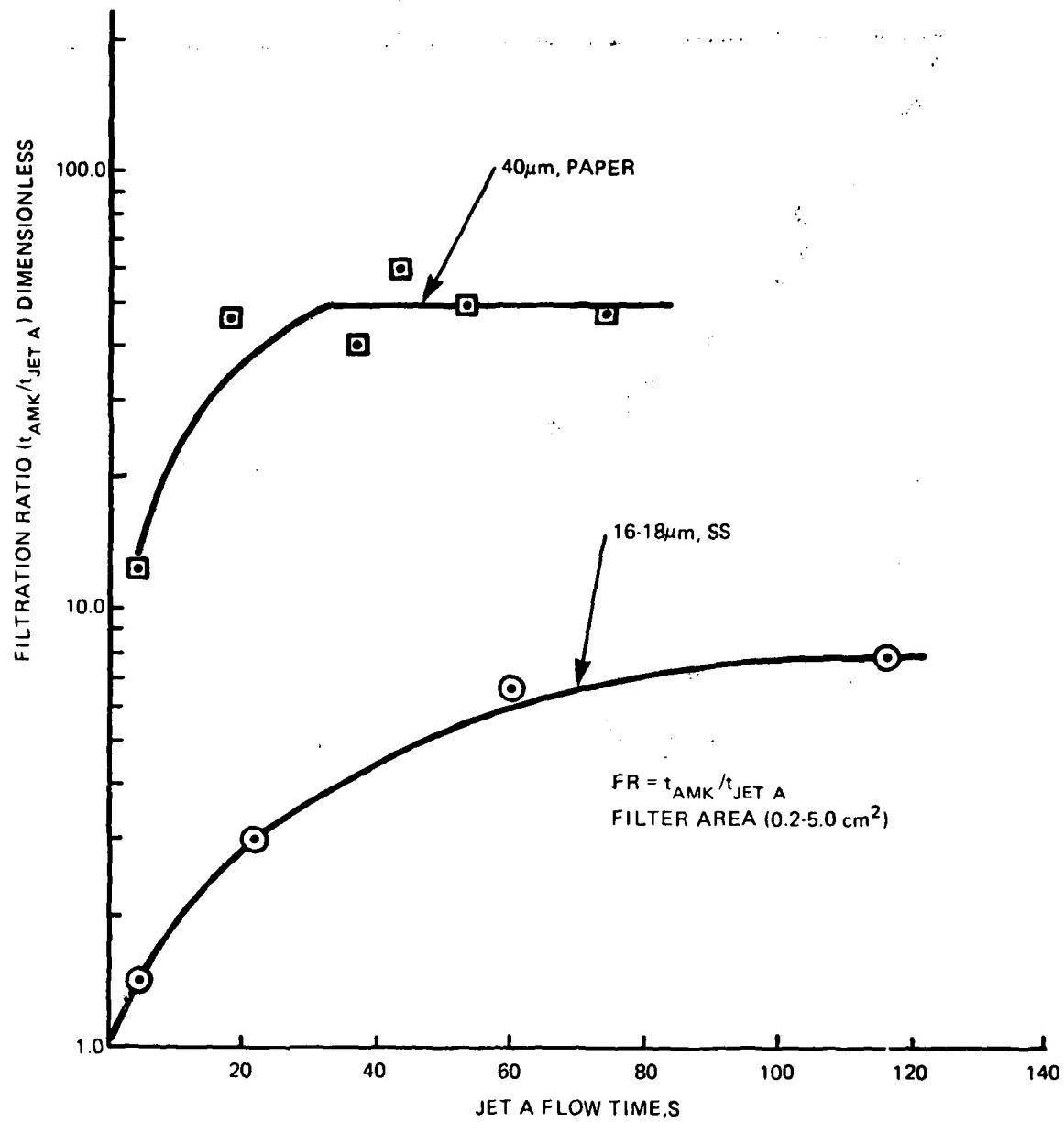
FIGURE 9-12. EFFECT OF FLOW TIME (AREA) ON THE FILTRATION RATIO
OF DEGRADED AMK IN TWO DIFFERENT FILTERS
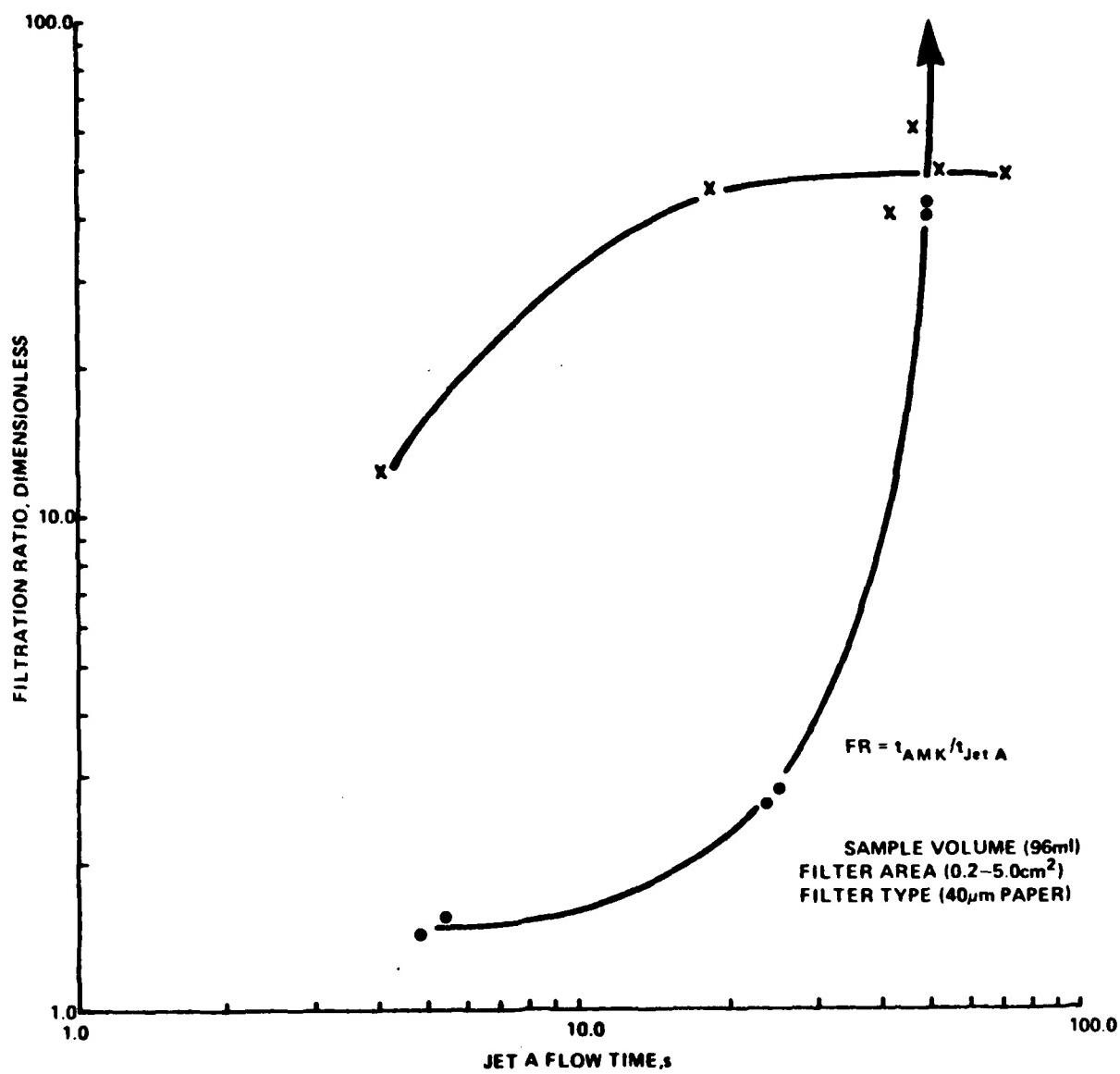
FIGURE 9-13. EFFECT OF JET A FLOW TIME ON THE FILTRATION RATIOS OF DEGRADED AMK
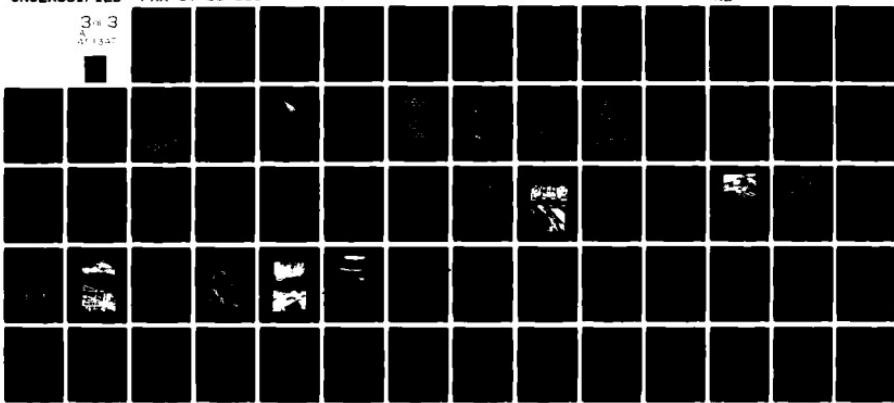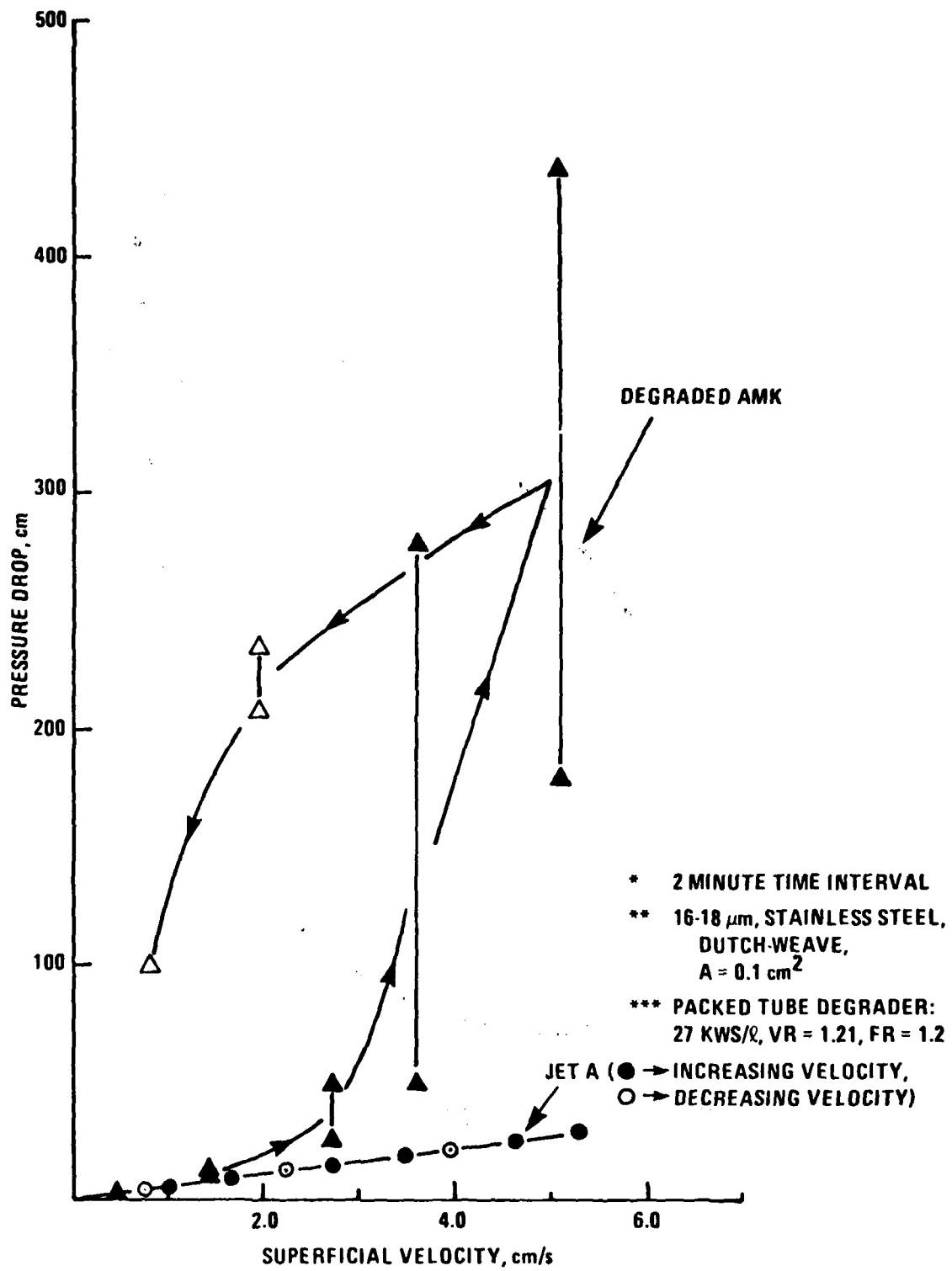
FIGURE 9-14.   EFFECT OF SUPERFICIAL VELOCITY ON PRESSURE DROP* ACROSS FILTER**
WITH JET A AND DEGRADED AMK***

9-22
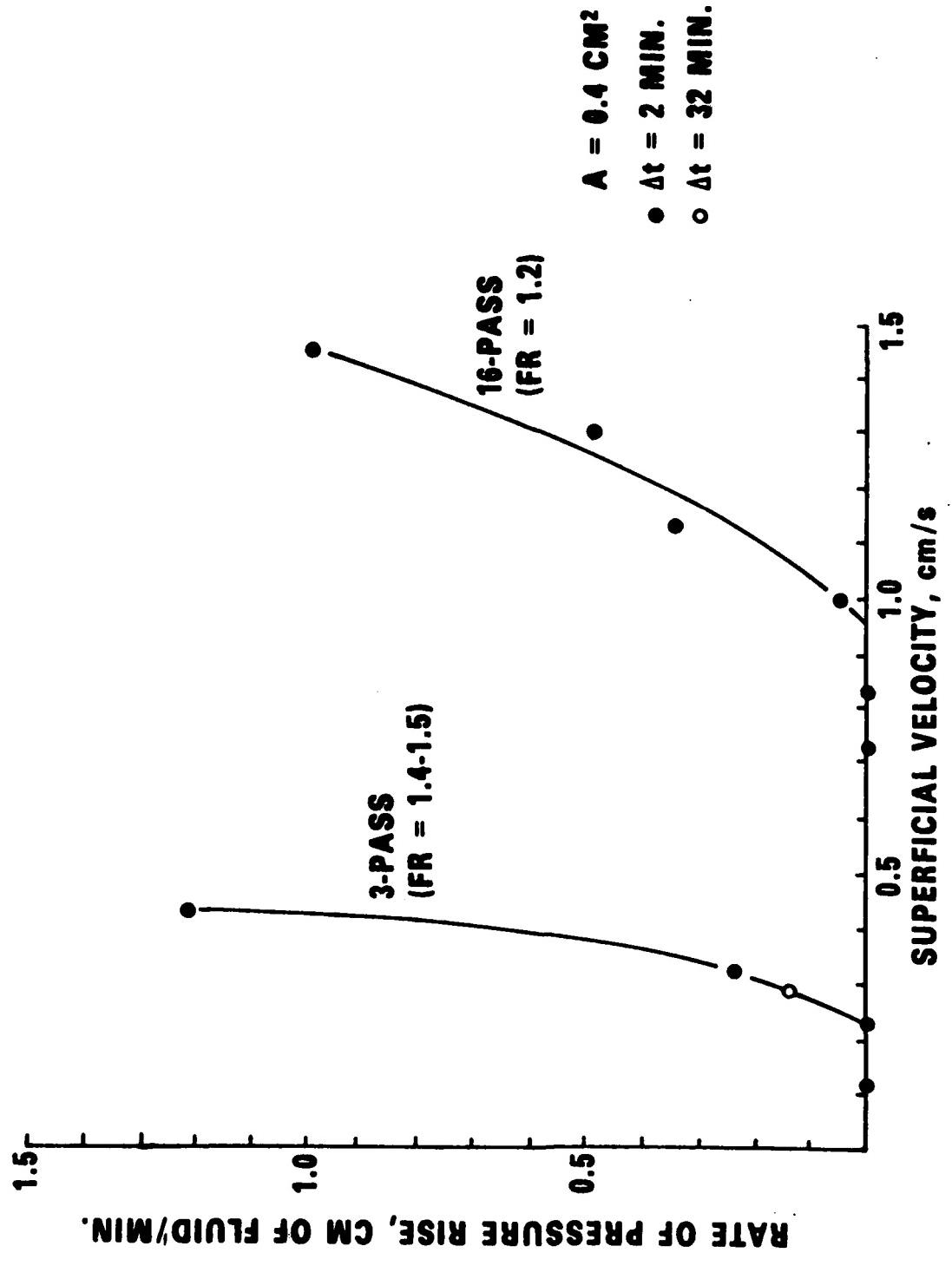
FIGURE 9-15. FILTER PLUGGING CHARACTERISTICS OF DEGRADED AMK (JT8D FUEL PUMP)
WITH 40 μM (P & W) PAPER FILTER
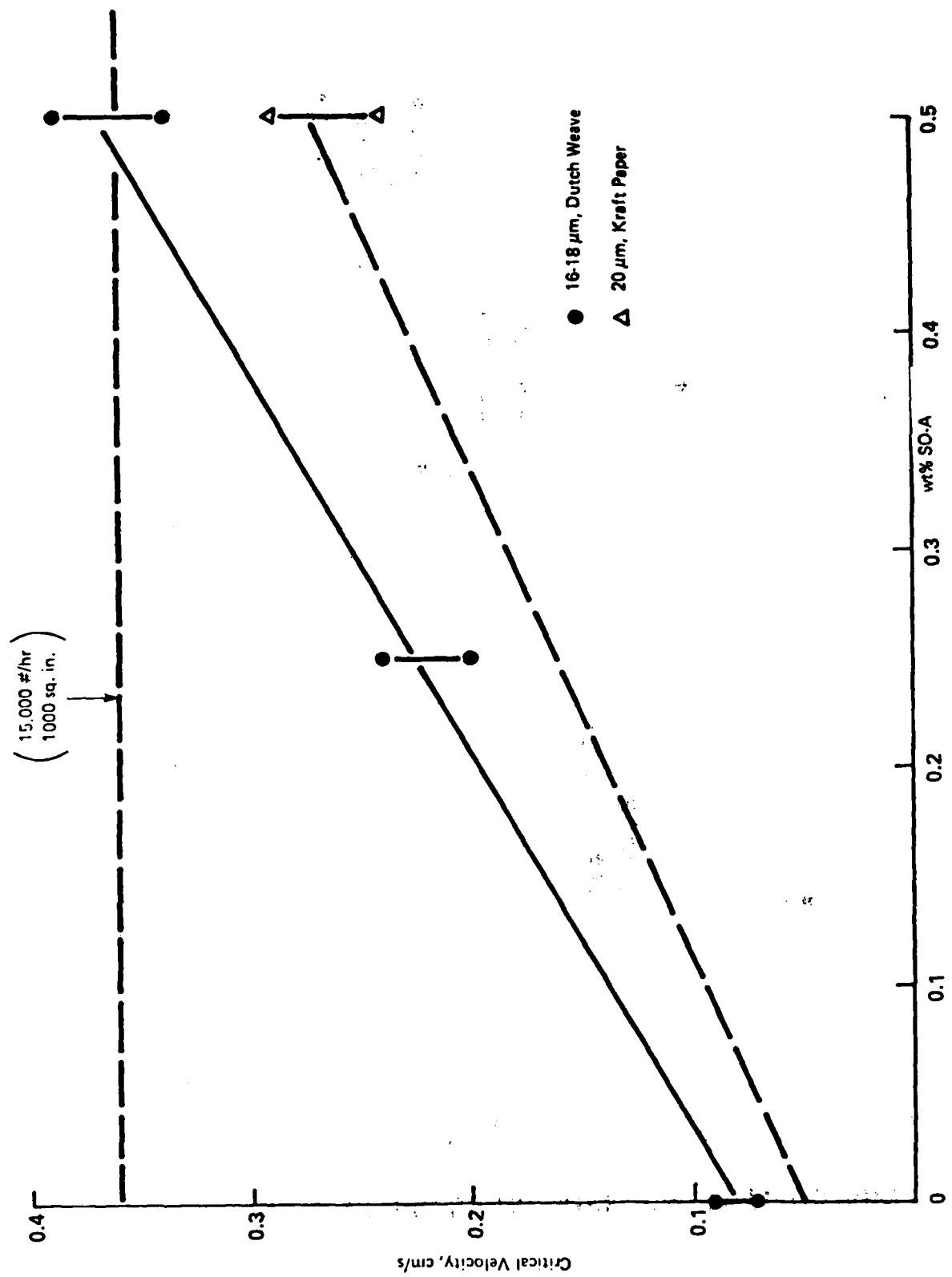
FIGURE 9-16.   EFFECT OF SURFACTANT ON THE CRITICAL FILTRATION VELOCITY OF UNDEGRADED AMK

9-24
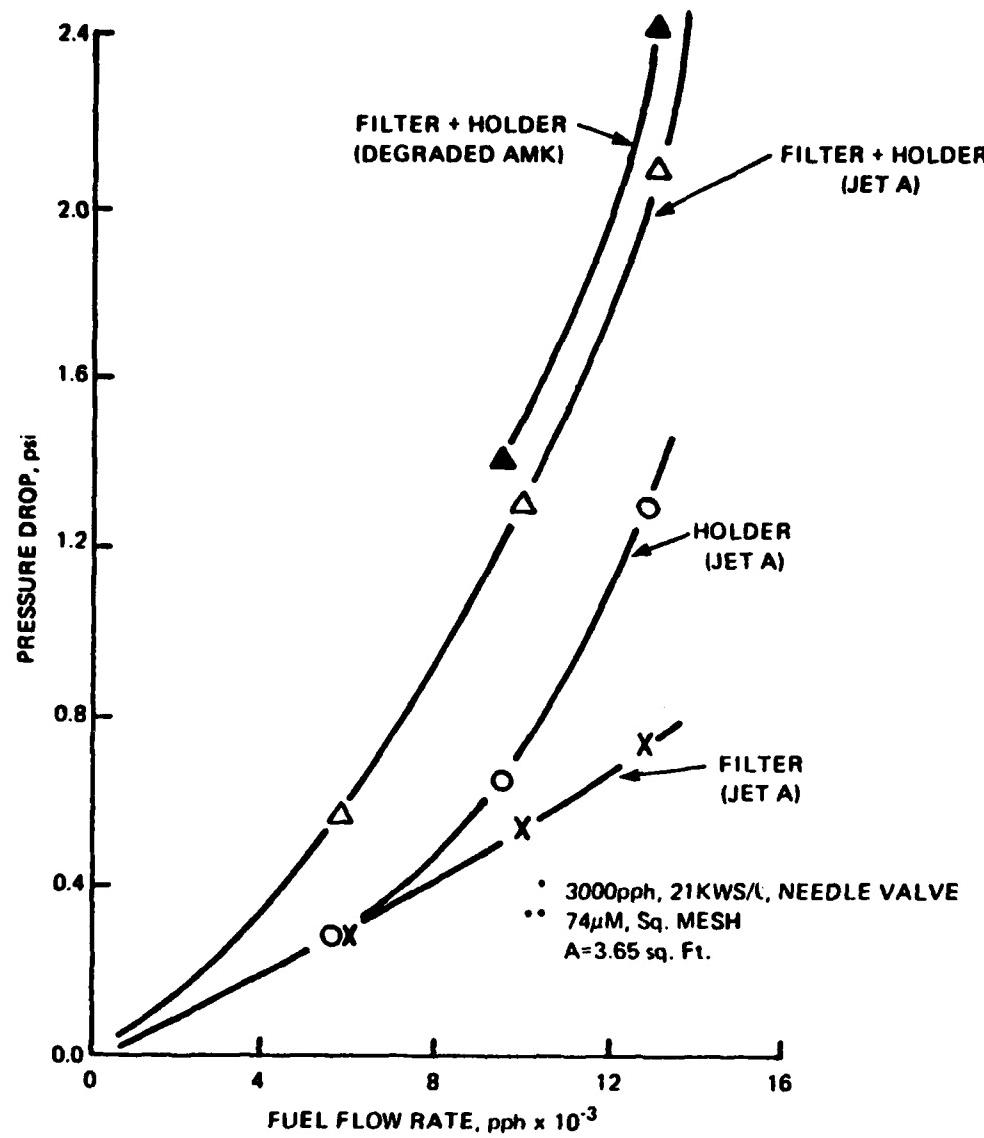
FIGURE 9-17.   FUEL FLOW RATE

Questions and answers following "Restoration and Characterization of Antimisting Fuel"

Discussions:

Mr. Zakai: Jack Zakai, Ohio State University. I was wondering whether you had done or planned to do any measurement of the molecular weight distribution of the polymers as they degrade. I know in experiments that we have done in the past, that looking and following the molecular weight distribution is very revealing in telling you what's really happening; and some of the apparently anomalous results with the various filters may be explainable. I know we had some normal stress measurements and some drag reduction measurements on degraded samples that we couldn't explain until we got some gel permeation chromatography (GPC) data, and that was very helpful.

Mr. Mannheimer: We're starting to do that. Our experience has been that for unintentionally degraded AMK GPC doesn't tell you much, slight degrees of degradation are hard to determine. It's been my experience that GPC is great for materials that have a molecular rate of a half a million; but if you get in a molecular range of 5 or 10 million, they seem to let you down a little bit, particularly with the high end of the molecular weight range. In some ways, it tells you some things, and then again, it will tell you something that you can't understand; that you have to go back and think about. An example of that is the slurry blended fuel. We have simulated this by blending it by hand. Our critical filtration velocities are very slow at our maximum power levels. Unfortunately, the GPC says we have a very high degree of degradation; even higher than systems that show much higher critical velocities.

Mr. Neidelman: Bill Needelman, Pall Corporation. There has been a trend which started a number of years ago in the commercial aircraft industry to go towards the disposable filters and finer filters for a number of reasons; the economics of disposables as opposed to cleanable filters and the general feeling that mechanical systems perform better and last longer if they have cleaner fluids. From your data, it seems that those types of disposable filters are more sensitive to this gelling. That may change in the future as we look at different filter materials. But my point is that if, as you indicated, and as JPL indicated, the gelation is not necessarily related to the antimisting properties, that may be a key point to work on in the future; the idea of removing the gelling or inhibiting the gelling properties.

Mr. Mannheimer: There was one thing I forgot to mention about the fact of adding a surfactant which allowed filtration without degradation of the sample. The cost is poorer low temperature characteristics, because the surfactant causes the polymer to swell more and pushes it into a more viscoelastic regime. There are some low temperature studies that show the polymer with the surfactant did not have as good low temperature pumping characteristics as the FM-9. Some low temperature problems may be introduced in place of the gellation.

ANTIMISTING FUEL TEST CORRELATION ANALYSIS

By

L. MAHOOD AND R. TALLEY

FALCON R&D

Falcon Research and Development (R&D) is performing a 10-month program, sponsored by the FAA Technical Center, to study rheometric and flammability testing performed on antimisting fuels. The goals of this study are; (1) to correlate the data produced by these tests and, where this is not possible, (2) develop methodology which will lead to correlatable test data. We are exclusively concerned with antimisting and crash fireball avoidance capabilities of the fuels, and rheometric tests which may be related to these properties.

At 60 percent completion of our program, we can state the following:

1. The large-scale flammability tests are essential to conclusively prove the crash fireball avoidance capabilities of a given candidate antimisting fuel.

2. The small-scale flammability tests are useful to screen out antimisting formulations which are significantly inferior in crash fireball avoidance.

3. By exploiting recent advances in rheology, dynamic modeling, and instrumentation, we believe that methods for extensive correlations can be defined and successfully implemented.

This paper is divided into two sections. The first section discusses the range of experiments and phenomena involved. The second section delves in detail concerning antimisting fuel flow, breakup, and degradation.

SECTION I

In pursuing our objectives, figure 10-1, emphasis on flammability tests was placed on group 1, which involves the most modern and active test rigs — both large- and small-scale. Also considered were group 2 tests, which involved older large-scale rigs, more small-scale flammability rigs, and rheometric tests. Twelve tests comprise the two groups. In the course of our site surveys and searches, several other test rigs were found valuable and included for analysis.

It was obvious early in our program, that even with the ingenuity and rigor evident with individual test rigs designed and optimized for a particular purpose, test results were often not directly relatable to other rigs of a different scale, operating principles, or screening criteria. Hence, we have been concerned with methods whereby the test rigs' data products, particularly those of group 1, might be directly correlated. Referring again to figure 10-1, we can group all of our tests into "flammability" and "rheometry." The former requires another breakout by large- or small-scale tests. Our nterest in the rheometric tests focuses on those which give results which may ultimately relate to crash fireball avoidance.

Figure 10-2 is a distribution of types of tests among these two categories. The corelations we are developing are mainly semiempirical. The phenomena are far too complex for an analytical "exact solution" to the problem. In contrast, our understanding is such that we do not have to fall back on statistical methods exclusively.

An extremely valuable result of successful correlation of small- to large-scale flammability tests would be to enable the former to confidently predict large-scale results. This may reduce the expenditures for large-scale testing, although final qualifications at large-scale would, in our judgment, remain essential.

Likewise, a correlation to small-scale rheometric tests would greatly increase confidence in the quality of formulations and batches of antimisting fuels used for testing.

In sorting out the flammability tests, they share many if not all of the phenomenological elements given in figure 10-3. They are dynamic elements, presented in an approximate time sequence.

Airflow or an air jet is a convenient means employed by many rigs to use a static test article, such as a fuel pipe and wing section. This represents relatively quiescent ambient air with a moving aircraft spilling fuel into the slipstream. Figure 10-4 lists the applications of our study of the fundamental characteristics of free air jets employed over a wide range of scales for static test articles. Figure 10-5 is a nondimensional schematic of the free turbulent jet. On this, can be superimposed the relative locations of test articles, fuel jets, ignition sources, and combustion phenomena. Figure 10-6 introduces ground plane effects on an incompressible "wall jet."

A number of the rigs have opposed fuel and air jets (figure 10-7). This eases our problem of scaling, and represents the most severe relative velocity for any given set of absolute fuel and air velocities. In cases where the fuel plume is more closely bounded, the impingement can be related to a proximate ground plane.

We are reassured to note that the critical interaction of the opposed fuel and air stream is typically in the "core flow" of the air jet, with relatively minor temporal and spatial variations in air velocity.

Referring again to figure 10-3, the next two phenomenological elements are "liquid breakup" and "droplet configuration and dispersion." These phenomena are so critical that a major portion of our study effort has concentrated upon their semi-empirical analysis and modeling. This is detailed in section II of this paper.

The crux of our correlation approach is that the output of both the semiempirical liquid breakup analysis and related experiments must be quantitative data on the mist cloud that forms. Fortunately, instrumentaion is available which can rapidly and efficiently quantify droplet size ranges and number densities in the ranges important to antimisting fuels. Work has been done in the past and is currently underway involving antimisting fuel spray imaging.

Qualitative evidence of both flammable and nonflammable fuel sprays abound. In some instances, flammable sprays could not be generated with neat jet A even at high speed until the fuel jet was narrowed. This indicates that although the

droplets were small enough for ignition, they were too widely separated (i.e., low number density). Heterogenous spray clouds have also been observed, wherein the "early" spray generated at high speed is fine enough for ignition, but is too widely dispersed. Conversely, the "later" spray at low speed is coarser but less dispersed, hence flammable.

The direct measurement of spray droplet sizes and number densities not only provides for correlation with breakup-related parameters and analysis, but is also an essential input into semi-empirical ignition/combustion models. The phenomena of heating, ignition, and propagation are highly dependent upon the fuel droplet spectra. Figure 10-8 lists important parameters and phenomena related to the ultimate criterion of fireball avoidance.

A variety of ignition sources has evolved to cover the range of extremes to be encountered in a survivable crash. They are being individually considered in the data correlations.

In some cases, antimisting fuel burning has been described as involving an obvious "entrainment." This given rise to our consideration of "external group combustion" (item B, figure 10-9), in addition to the more commonly postulated "internal group combustion" (item A).

The output of the flammability tests involves careful study of the criteria for acceptable and unacceptable performance of a given test fuel. Figure 10-10 lists the various observed phenomena that have been utilized. We are attempting to fit these into more general and possibly quantifiable semi-empirical relationships. The large-scale and controlled crash tests provide the most clear-cut and credible criteria — against which the small-scale pass/fail criteria must be judged.

In looking at our program comprehensively, seven priorities have clearly evolved. They are listed in our judged order of importance in figure 10-11.

The first four times are being simultaneously addressed by our emphasis on fluid flow, breakup, and degradation analyses. Item 5, aerodynamic characterization, becomes significant only after the major correlations are achieved, and will enhance test accuracy, repeatability, and fit of combustion modeling and pass/fail criteria (item 6).

Finally, if the higher priority items are satisfied, it remains important to define the thermal limits (if any) of performance of antimisting fuels given crash scenarios involving high bulk fuel temperatures and high to extreme ambient air temperatures.

SECTION II

Figure 10-12 shows our objectives in examining the rheology and breakup of antimisting fuels. In reviewing existing work on fuel rheology, particular attention is being given to what is measured versus what is needed to characterize fluid behavior in expected situations of flow, breakup, and degradation. It is recognized that no known single measurement technique is apt to be appropriate to yield all the rheological parameters needed. Accordingly, our rationale for technique examination involves two considerations — near-term and long-term. For the

near-term, more detailed fluid properties are desired to better understand key mechanisms and to correlate selected properties with operational performance features of antimisting fuels. For the long-term, selected fluid properties are desired which correlate with overall fuel performance and therefore can be used for quality control of the fuel.

For fuel breakup, the emphasis is on clarifying the nature of the breakup process and in exploring the utility of liquid breakup models in correlating flammability test data. Liquid breakup itself, is recognized as a complex process. We also believe it is an important one to data correlation, through its impact on results in tests of different scale.

The breakup process depends not only on the properties of the liquid, but also on the size of the frontal surface of liquid exposed to the airstream, and on the magnitude of the relative air velocity. Further, the process may change with scale since different mechanisms can be involved in test configurations of different sizes.

We view liquid breakup as an intermediate step in establishing data correlation. Once this correlation is established, it is probable that the breakup phenomena can be circumvented and the flammability results can be directly related to the reheological properties of the treated fuel.

Figure 10-13 indicates several known types of breakup involving liquid drops and jets. For present purposes, dumbbell oscillation and bag breakup are relatively unimportant. With viscoelastic liquids, bag formation may occur, but typically the bag ruptures, deflates, and coalesces back into a single drop — rather than forming a number of separate droplets. Both stripping and Taylor breakup are important in antimisting fuel considerations.

These last two types are indicated as indivudal mechanisms in figure 10-14. Both of these have been studied experimentally and theoretically, and are discussed in the literature.

Stripping is the mechanism of key importance in most cases of aerodynamic breakup of liquids. This scheme is somewhat idealized in the figure, but involves wind-induced instability in the liquid and rapid growth of the spectrum of waves. Ligaments typically break off from the wave crests and undergo further breakup to form drops. If these primary drops are large and the relative velocity is high enough, the drops may break again. The drop size in primary breakup is related to the length of the wave from which it originated.

Taylor breakup involves the instability and rupture of an extended liquid surface due to an acceleration directed from a less dense into a more dense material. Here it appears as a deceleration of the liquid fuel relative to air. Taylor breakup occurs in situations where there is a proper combination of a large frontal surface and large relative air velocity. It is expected to be important in large-scale antimisting fuel tests.

Past antimisting fuel studies suggest that both shear and elongational viscosity may be important to the flow and breakup of these fuels. We believe that the elasticity properties which a polymer-enhanced fuel may exhibit at high strain rates are especially important to liquid breakup. From studies on other elastic

10-4

fluids, it is known that at low wind velocity the elasticity may give greater stability to the liquid towards breakup. At higher velocities, the shear (and possibly tensile) stresses are too large for the elasticity to prevent breakup.

One probable role of viscoelasticity (and fluid elasticity) in liquid breakup is indicated in figure 10-15. Here ligaments of antimisting fuel would be expected to thin and extend due to ligament motion in the air. If the material has significant elastic properties, it would be expected to break and the free ends of the thread retract upon themselves by elastic and surface tension forces to form liquid globules.

Figure 10-16 is included to show in the case of a near-breaking water wave that shear motion of the liquid is still involved in wave development. Then, it seems that both shear and perhaps tensile viscosity are important, as well as elasticity.

Figure 10-17 indicates schematically the flow and breakup phenomena expected to occur in the FAA Wing Fuel Spillage Test Rig.

Figure 10-18 shows an example of a mass-size distribution obtained experimentally for hot wax in a hot gas stream by Weiss and Worsham. The solid curve is the complete distribution predicted using a computer code for liquid breakup which has been put on-line at Falcon/Buffalo under an in-house effort. This model treats the aerodynamic breakup of a Newtonian or non-Newtonian viscoelastic liquid injected into a subsonic airstream, and is patterned after the early work of Mayer. For reasons of simplicity, this model is not fully predictive, but is phenomenological and requires that a few selected parameters be established to align predicted results with experimental findings. Once this is accomplished, model predictions can be used to explore breakup over a range of conditions. In the example shown, the model was matched to the experimental data at the massmedian diameter (MMD) of 70 m. The predicted shape results from a built-in uniform probability density over wavelength for wave formation.

Figure 10-19 shows predicted mean-size distributions for neat jet A fuel injected contrastream in the Spray Flammability Test Apparatus. One calculated MMD was used for matching the model-generated distributions.

While the model has been used previously in conjunction with the breakup on non-Newtonian elastic liquids, similar calculations for antimisting fuels have not been carried out under this program. There are several reasons for this. First, the comptuer codes do not presently contain the physical model for Taylor breakup. Second, the existing data base of information on antimisting fuels is inadequate, particularly regarding the drop-size spectra produced in representative tests and the elasticity properties of the fluid.

A spin-off from examining the mechanistic aspects of liquid breakup is an indication of what rheological features are apt to be important. While shear and elongation viscosities are relevant, it seems that the rather elusive property of fuel elasticity is especially important in breakup. Experience with breakup of other types of viscoelastic liquids suggests that perhaps even a simplified elasticity characterization, such as recoverable strain, may offer a useful avenue of approach.

Figure 10-20 shows a schematic layout of the Haake Rotovisco viscometer with an attachment for measuring the recoil of elastic fluids to evaluate recoverable shear strain.

10-5

Figure 10-21 shows a schematic of the Weissenberg Rheogoniometer. It is my under-
standing that this classic cone and plate unit is not particularly useful in
evaluating antimisting fuels.

Figure 10-22 shows several rheometer schemes which have been explored for measuring
elongational flow properties of antimisting fuels. The pendant drop and open-
siphon techniques yield interpretable results in a more straightforward manner than
the screen or converging flow schemes. A significant feature of the pendant drop
scheme is that with it, elongational viscosity can be measured in the millisecond
time regime appropriate to drop breakup. It also appears that this scheme could be
used to evaluate recoverable elongational strain.

In summary, the correlation of flammability data, in terms of fuel properties,
appears much more amenable if the breakup of the fuel is taken into consideration.
Ultimately, the breakup aspect may be able to be circumvented. While liquid
breakup is complex, a model does exist which may serve as a basis for test data
correlation. Explanation of the full utility of the model in this role will
require further data and information regarding fuel rheology and selected breakup
results. Also, some additional model modifications appear necessary in order to be
able to apply it over the range from small-scale experiments to full-scale crash
tests. We are optimistic that such developments can provide the FAA with a tool
for characterizing the breakup behavior of candidate fuels over a wide range of
operating conditions and test scales.

- CORRELATE FLAMMABILITY TEST DATA

  - •• GROUP 1 TESTS
  - •• GROUP 2 TESTS
  - •• OTHER TESTS

- DEVELOP CORRELATABLE TEST METHODS

  - •• FLAMMABILITY
    - ••• LARGE–SCALE
    - ••• SMALL–SCALE
  - •• RHEOMETRY

FIGURE 10–1.   PROGRAM OBJECTIVES
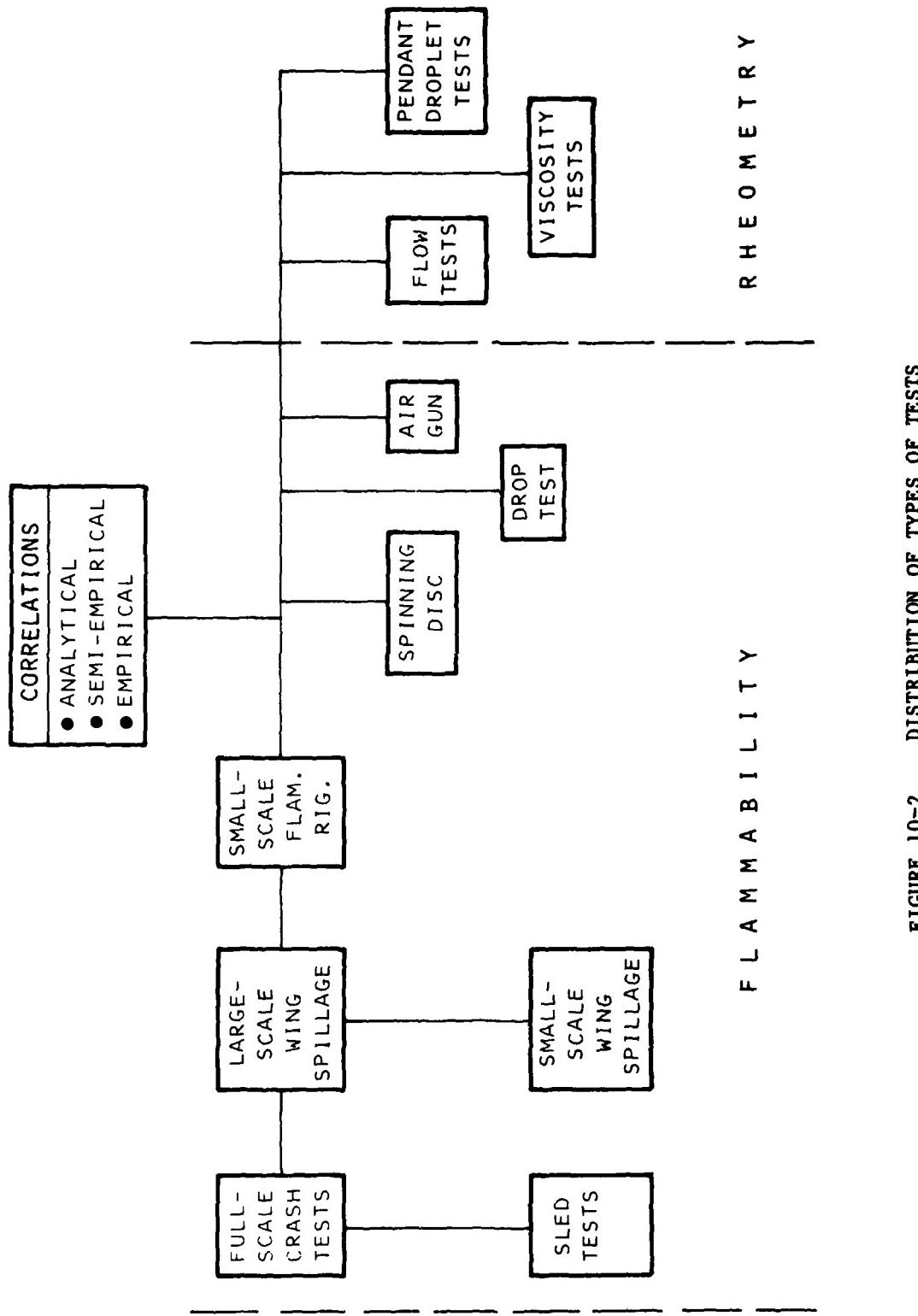
FIGURE 10-2.   DISTRIBUTION OF TYPES OF TESTS

AIR FLOW/JET

LIQUID FLOW/JET

LIQUID BREAKUP

DROPLET CONFIGURATIONS & DISPERSION

HEATING

IGNITION

PROPAGATION (PASS/FAIL)

POOL IGNITION

FIGURE 10-3.   PHENOMENOLOGY ELEMENTS SHARED BY FLAMMABILITY TESTS

VELOCITY CORRELATION WITH DECELERATION TESTS

- LIQUID BREAKUP ANALYSIS
  - Droplet Characterization
- AMK HEATING AND IGNITION
- FLAME PROPAGATION
  - Pass/Fail Criteria
- GROUND-PLANE EFFECTS
- CHARACTERIZATION PROCEDURES
  - Flow
  - Turbulence

FIGURE 10-4.   FUNDAMENTAL CHARACTERISTICS OF THE FREE-AIR JET STUDY
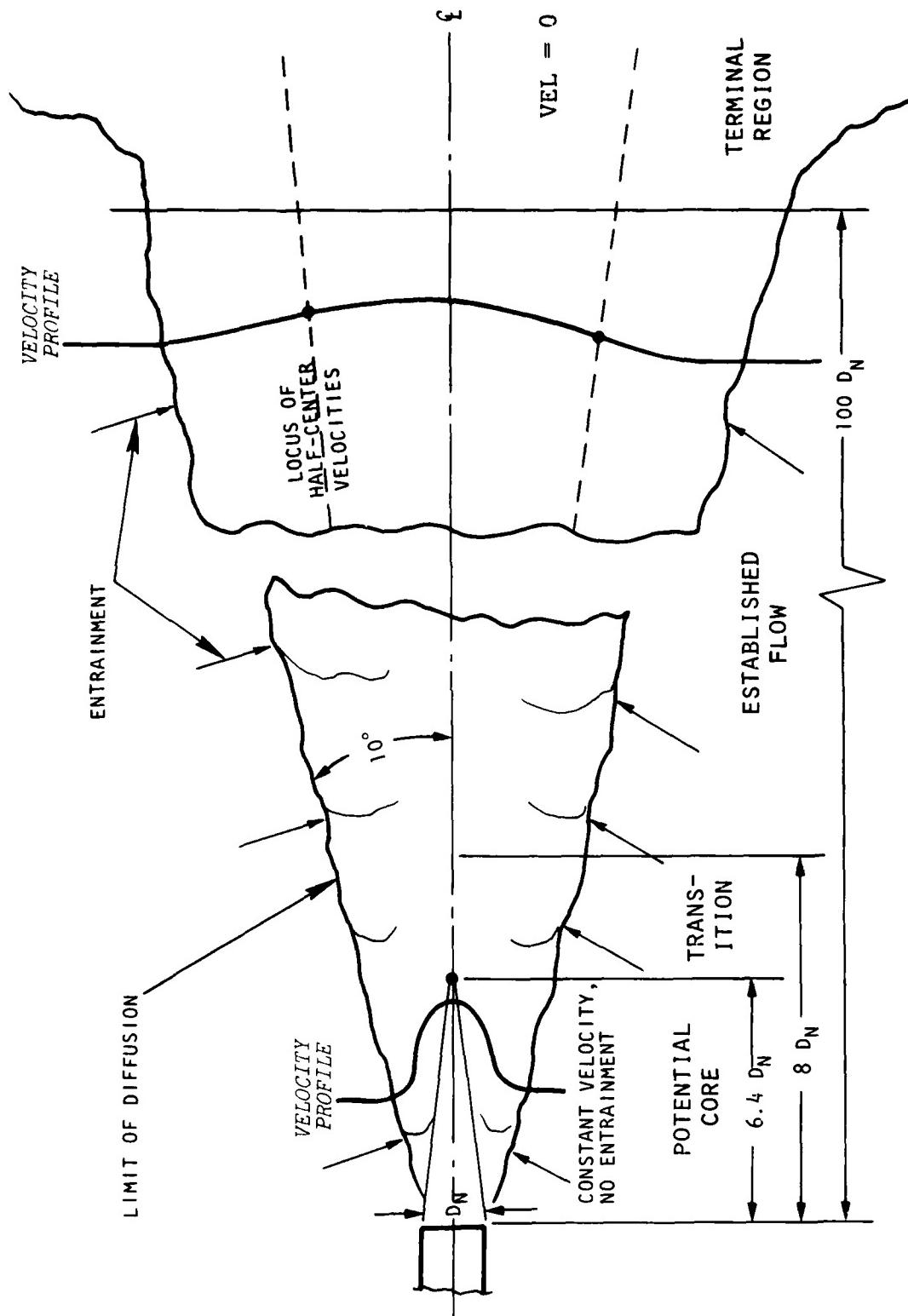
FIGURE 10-5.   FREE TURBULENT JET
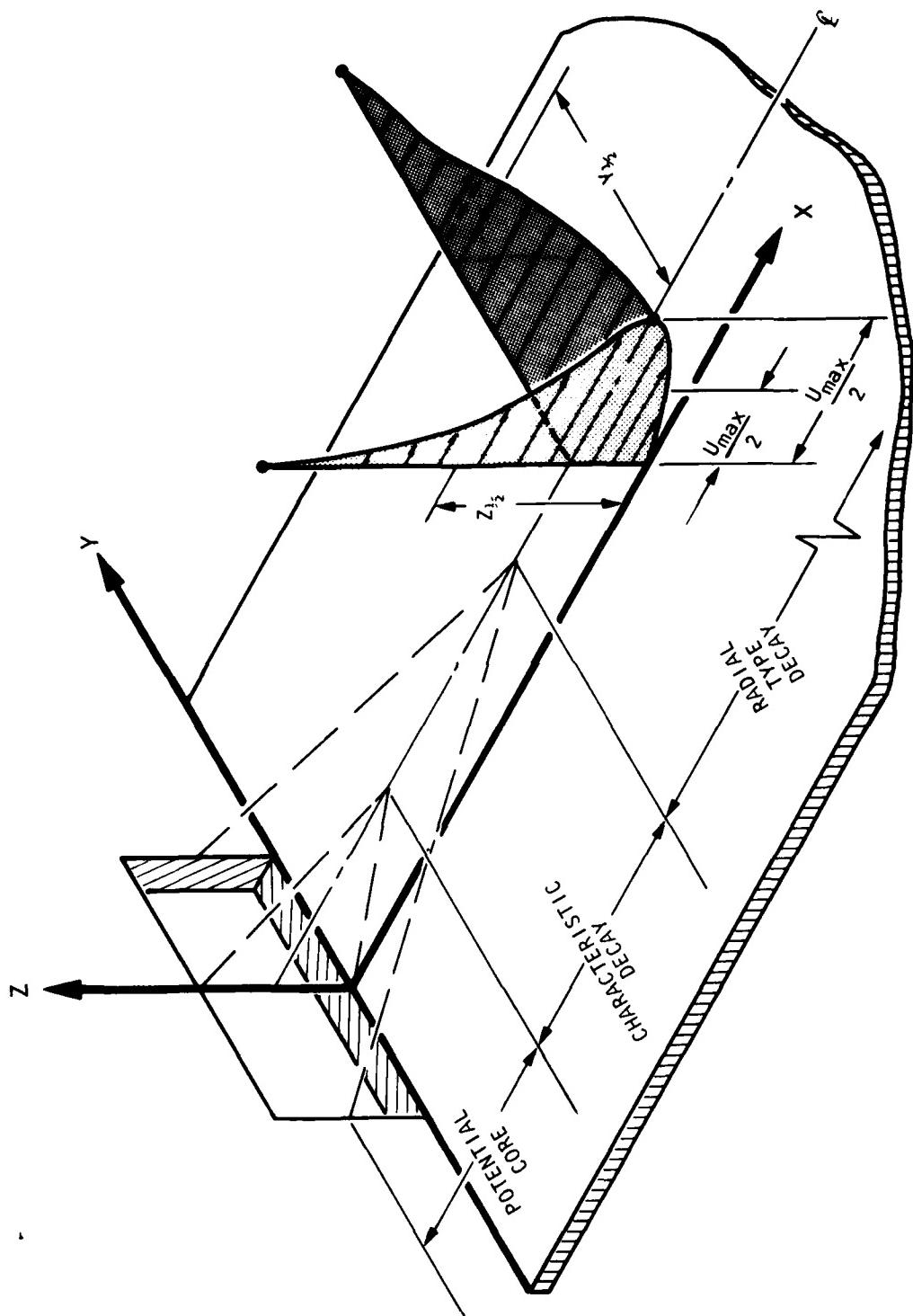
FIGURE 10-6. 3-D, INCOMPRESSIBLE WALL JET
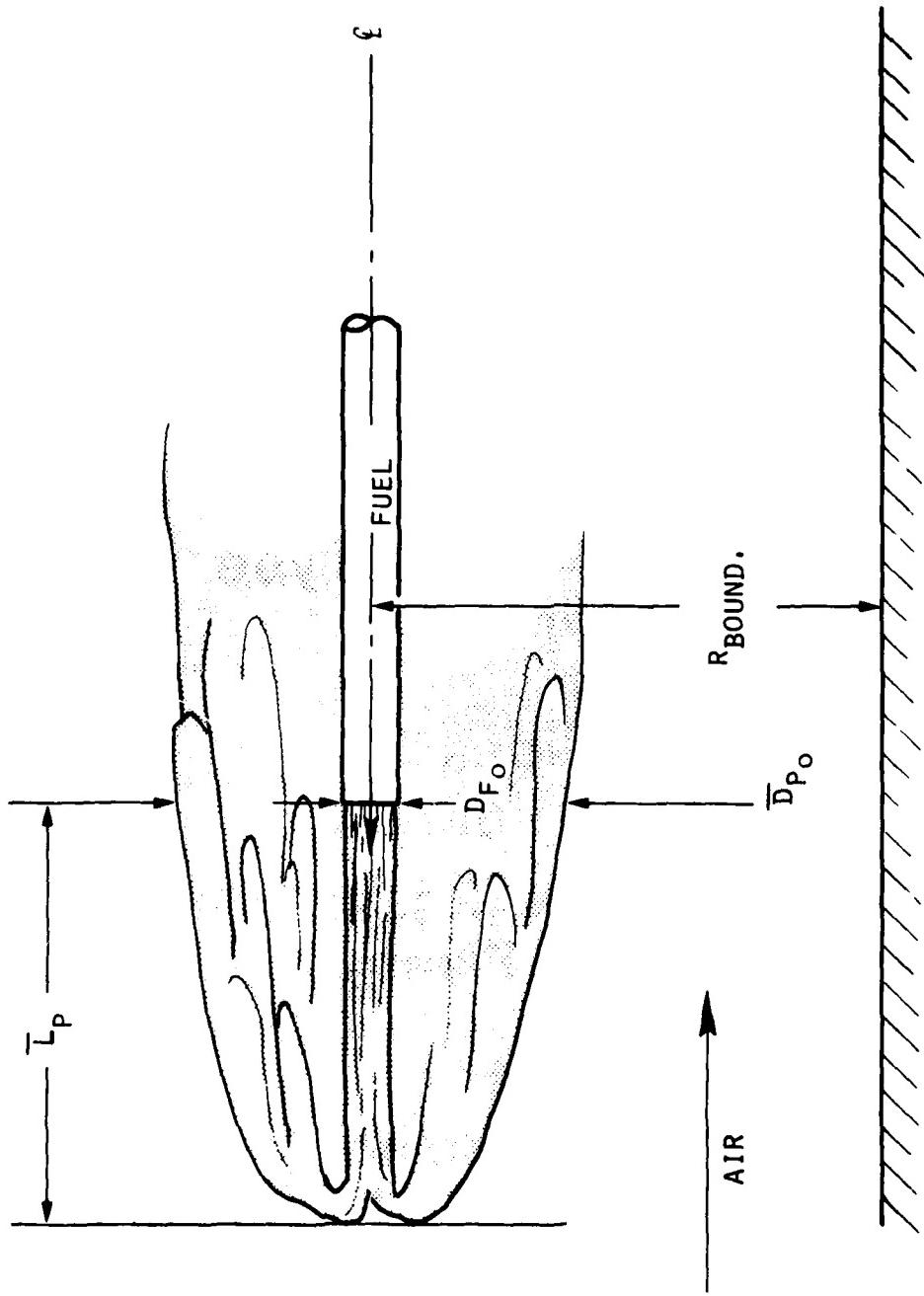
FIGURE 10-7.   OPPOSED FUEL AND AIR JETS

FUEL TEMPERATURE
AIR TEMPERATURE
HEAT/IGNITION SOURCES
- **Heating**
    - •• Negligible
    - •• Low
    - •• Moderate
    - •• High
- **Size**
- **Configuration/Type**
- **Location**
- **Number**
- **Interactions**
- **Time Variations**

PROPAGATION (Pass/Fail)
- **Diffusion Flame**
    - •• Vapor
    - •• Droplets
- **Cluster Burning**
- **Entrainment, Turbulence**

FIGURE 10-8.   HEATING, IGNITION, PROPAGATION
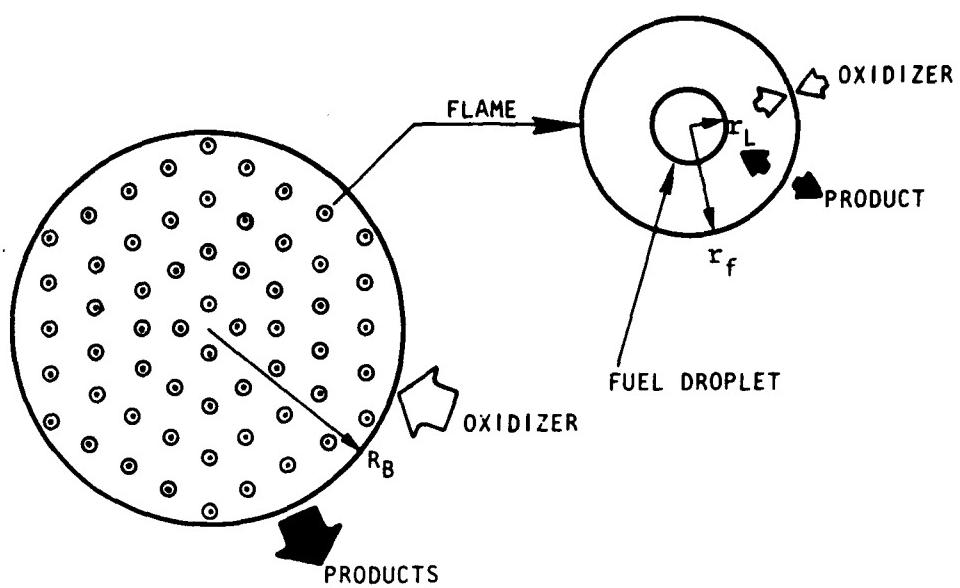
A.   INTERNAL GROUP COMBUSTION
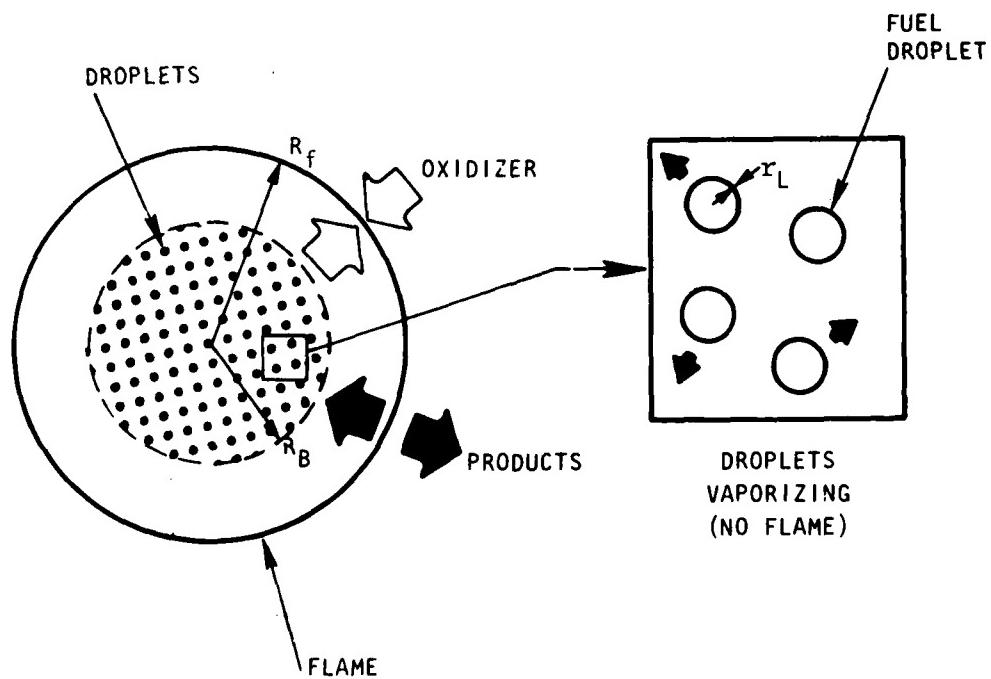
B.   EXTERNAL GROUP COMBUSTION

FIGURE 10-9.   DROPLET COMBUSTION MODES

RATE OF PROPAGATION (Size Increase)

SIZE

WAKE FLAME SIZE INCREASE

DETACHMENT FROM WAKE FLAME, SIZE

POOL INTERACTION/IGNITION

UPSTREAM PROPAGATION

ENGULFMENT

FIGURE 10-10.   PASS/FAIL CRITERIA

1. ON-SITE AMK CHARACTERIZATION
- • Batch /Mixing Control
- • Aging
- • Pre-, Post-Test

2. LIQUID BREAKUP CORRELATION

3. VELOCITY CORRELATION
- • Breakup
- • Pass/Fail
- • Concentration

4. DROPLET CHARACTERIZATION

5. AERODYNAMIC CHARACTERIZATION

6. PASS/FAIL FLAMMABILITY CRITERIA

7. TEMPERATURE SENSITIVITY

FIGURE 10-11.   PRIORITIES

OBJECTIVES

EXAMINE CHARACTERIZATION OF FLUID PROPERTIES OF AM FUELS RELATIVE TO

- FLOW (THROUGH FUEL LINES, FROM CRASH FORMED ORIFICES, ETC.)

- LIQUID BREAKUP ASSOCIATED WITH CRASH RELEASE

- DEGRADATION OF FUEL ADDITIVES

EXAMINE BREAKUP PROCESS AND BREAKUP MODELS TO ESTABLISH

- RATIONAL BASIS FOR BREAKUP

- MODEL CAPABILITY TO HANDLE RHEOLOGICAL PROPERTIES OF AM FUELS

- UTILITY OF MODELS IN SCALING TEST DATA

FIGURE 10-12. AMF RHEOLOGY AND LIQUID BREAKUP

10-18

STRIPPING BREAKUP
(DROP AND JET)

TAYLOR BREAKUP
(DROP AND JET)

DUMBELL OSCILLATION
(DROP)
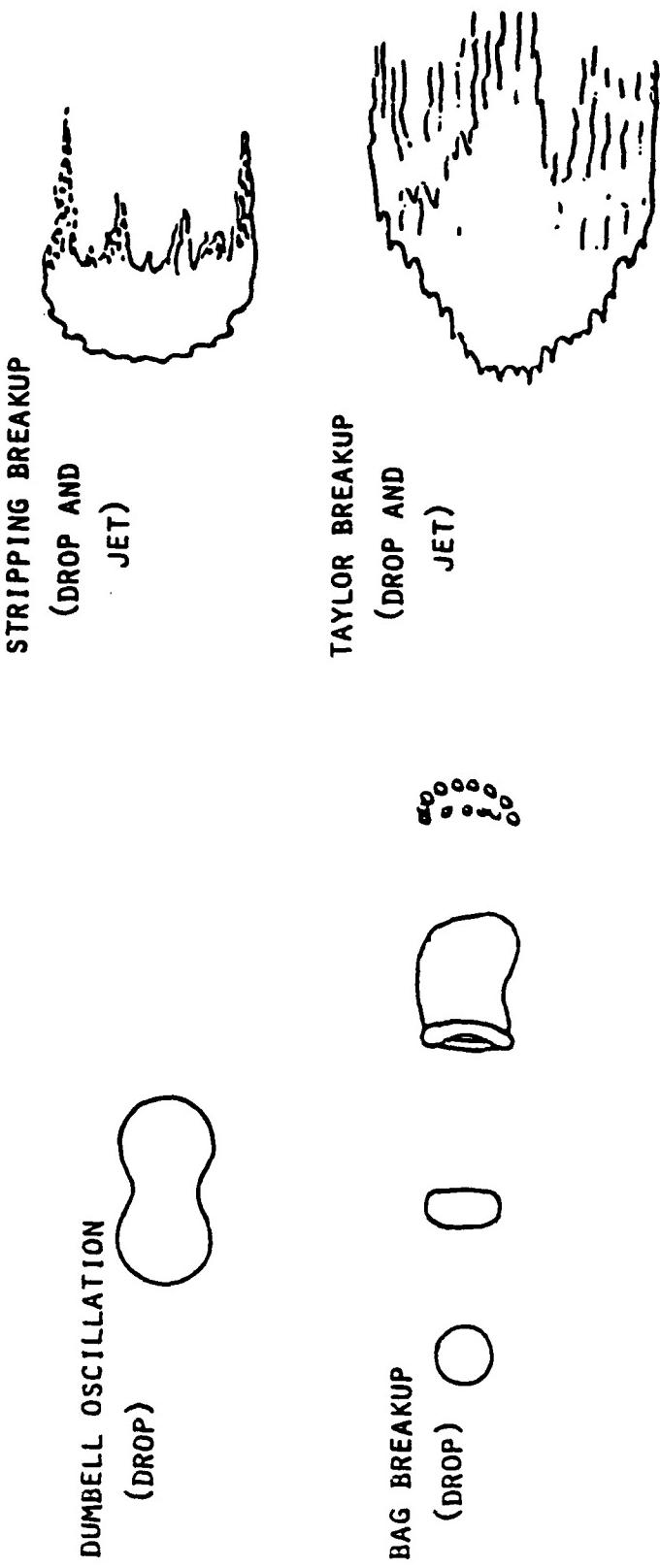
BAG BREAKUP
(DROP)

FIGURE 10-13. TYPES OF LIQUID BREAKUP

STRIPPING BREAKUP (SURFACE EROSION)

$d = F\lambda$

DROP

LIGAMENTS

λ

RELATIVE
WIND

TAYLOR BREAKUP

AIR BLOW THROUGH

RELATIVE
WIND
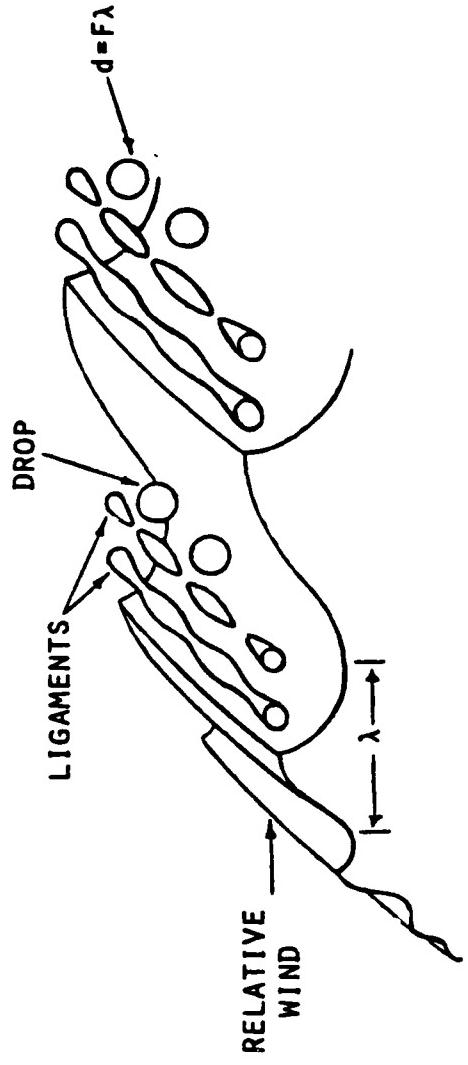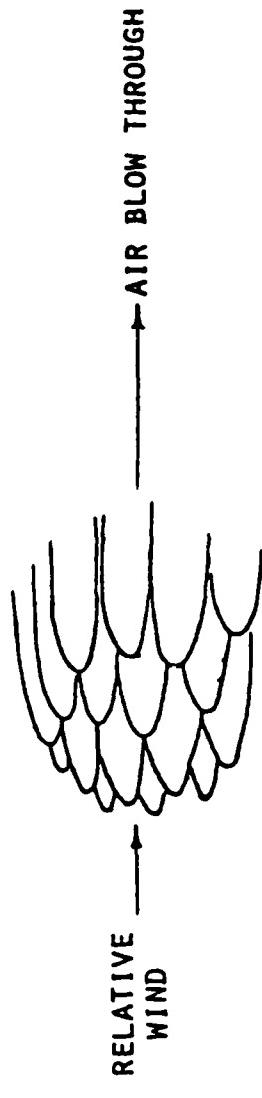
FIGURE 10-14.   BREAKUP MECHANISMS

LIGAMENT BREAKUP
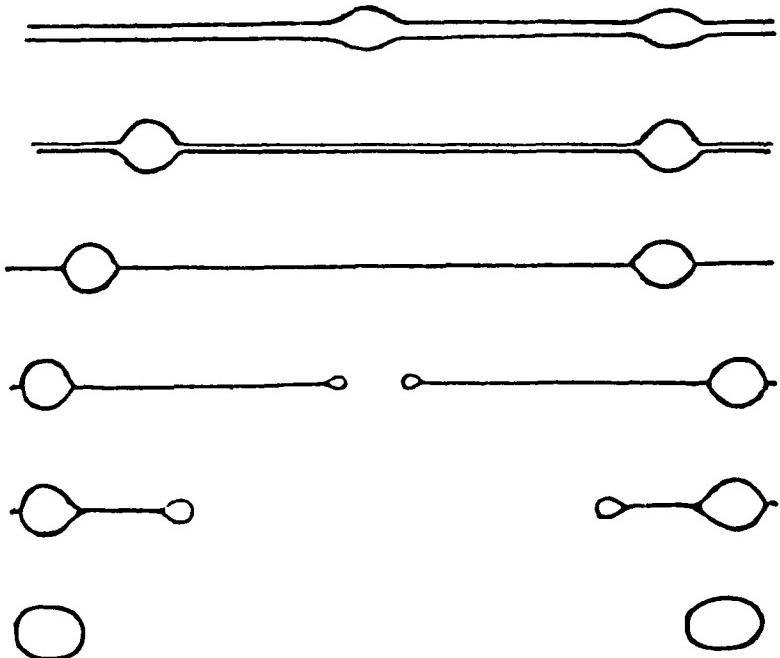
FIGURE 10-15.   PROBABLE ROLE OF VISCOELASTICITY IN BREAKUP
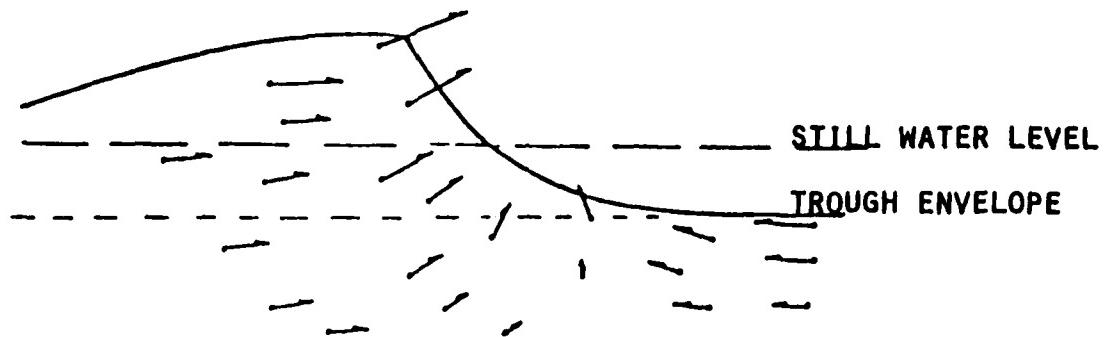
FIGURE 10-16.   PARTICLE MOTION WITHIN A WATER WAVE
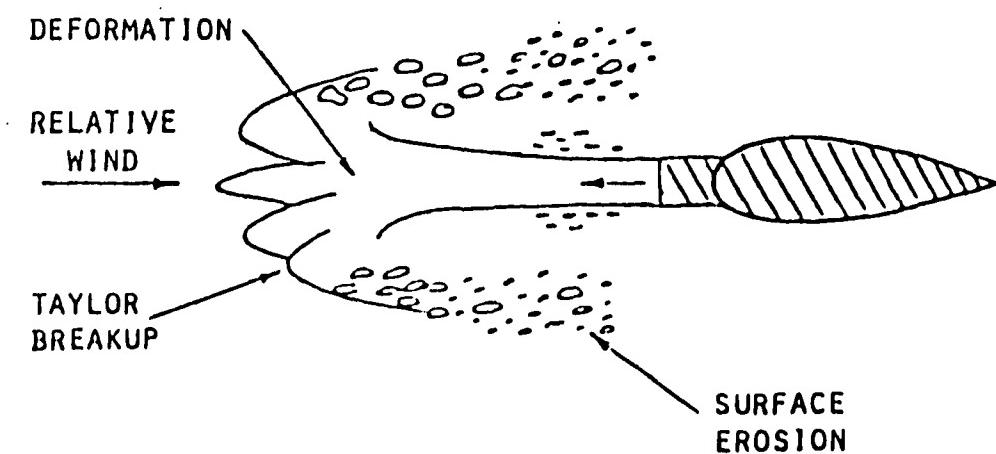
FIGURE 10-17.   LIQUID BREAKUP IN WING-FUELS SPILLAGE CONFIGURATION (PRELIMINARY)
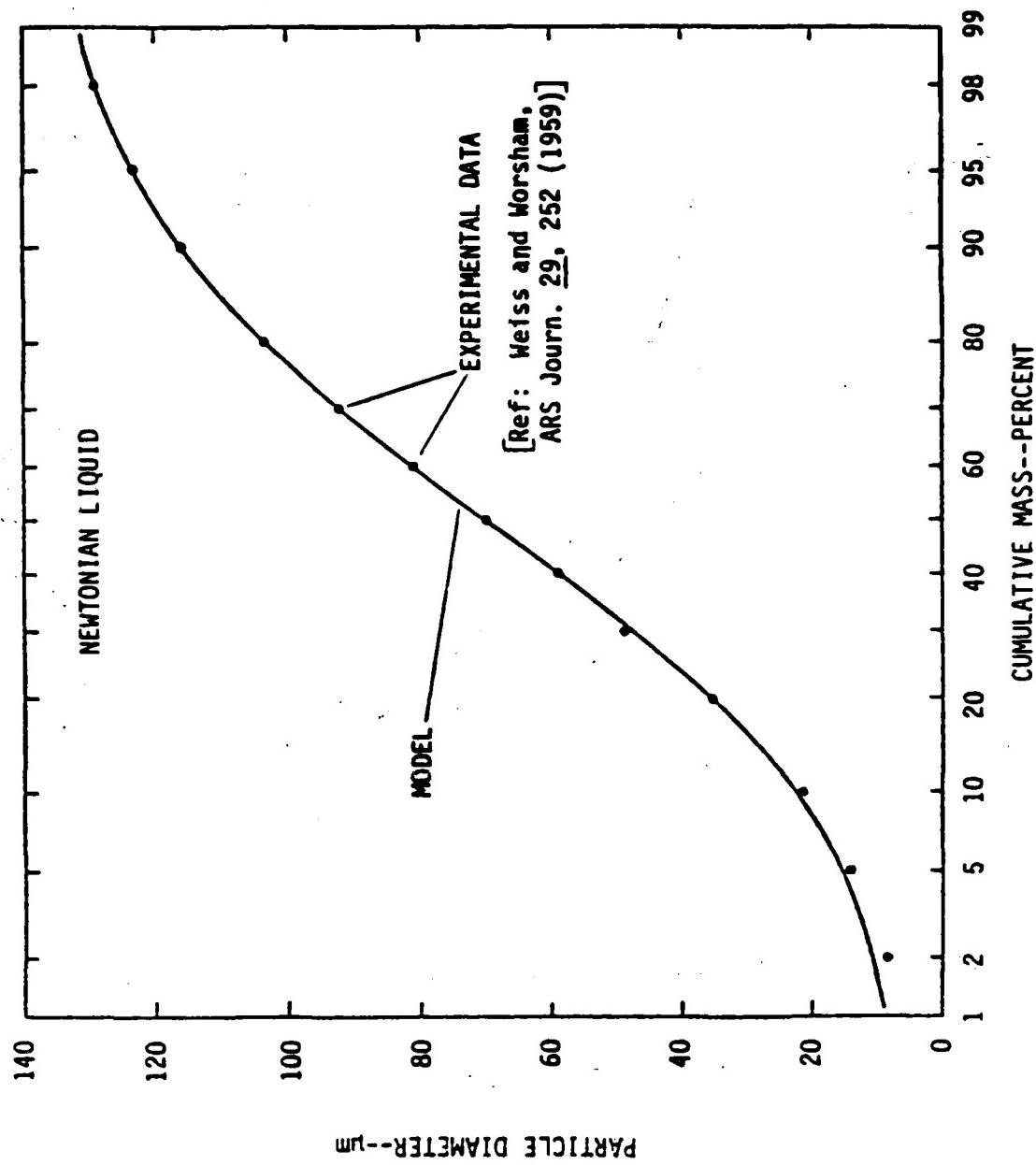
FIGURE 10-18.   BREAKUP MODEL PREDICTION VERSUS EXPERIMENTAL DATA
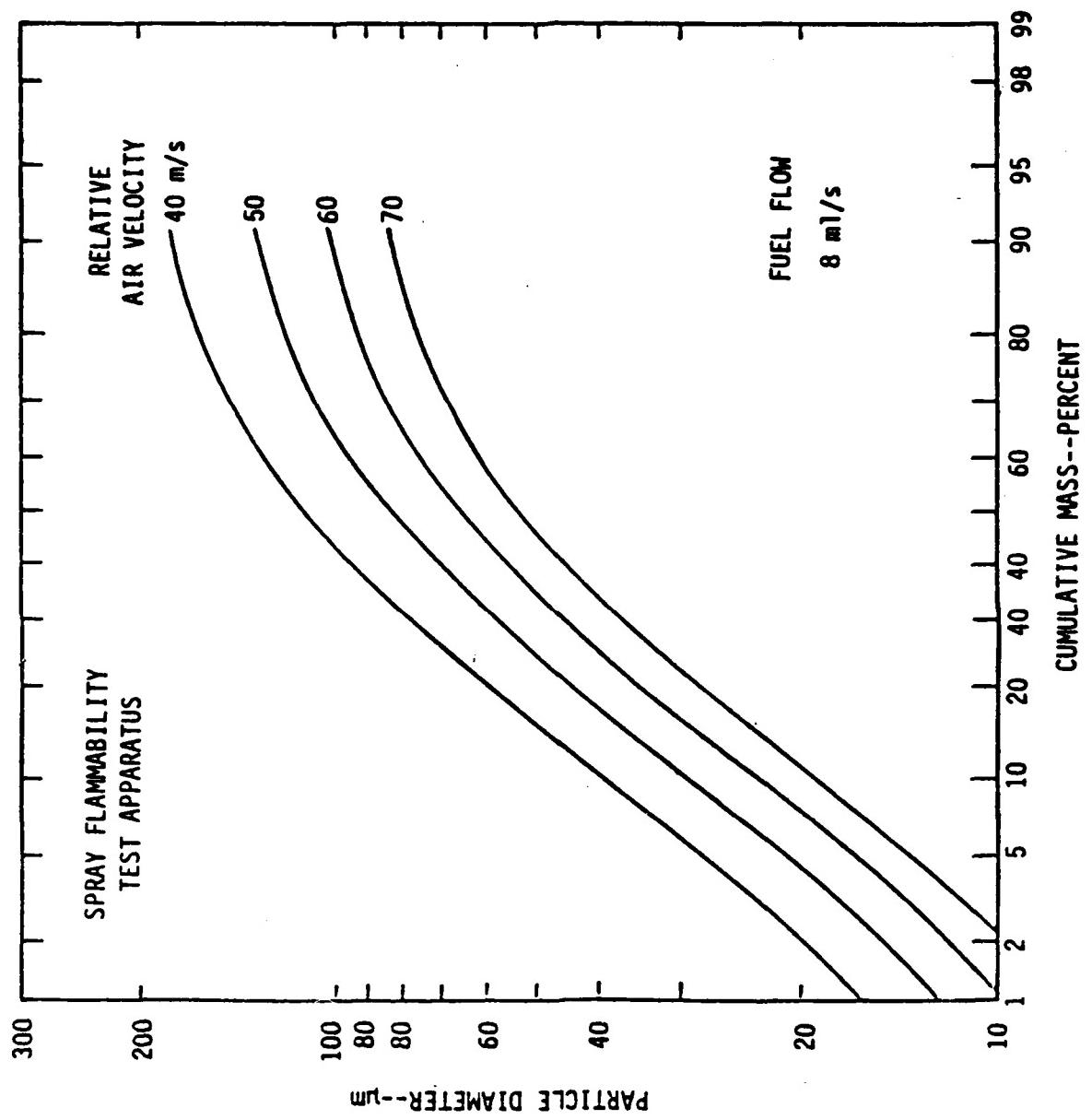
FIGURE 10-19. NEAT JET A DROPLET DISTRIBUTION PREDICTIONS
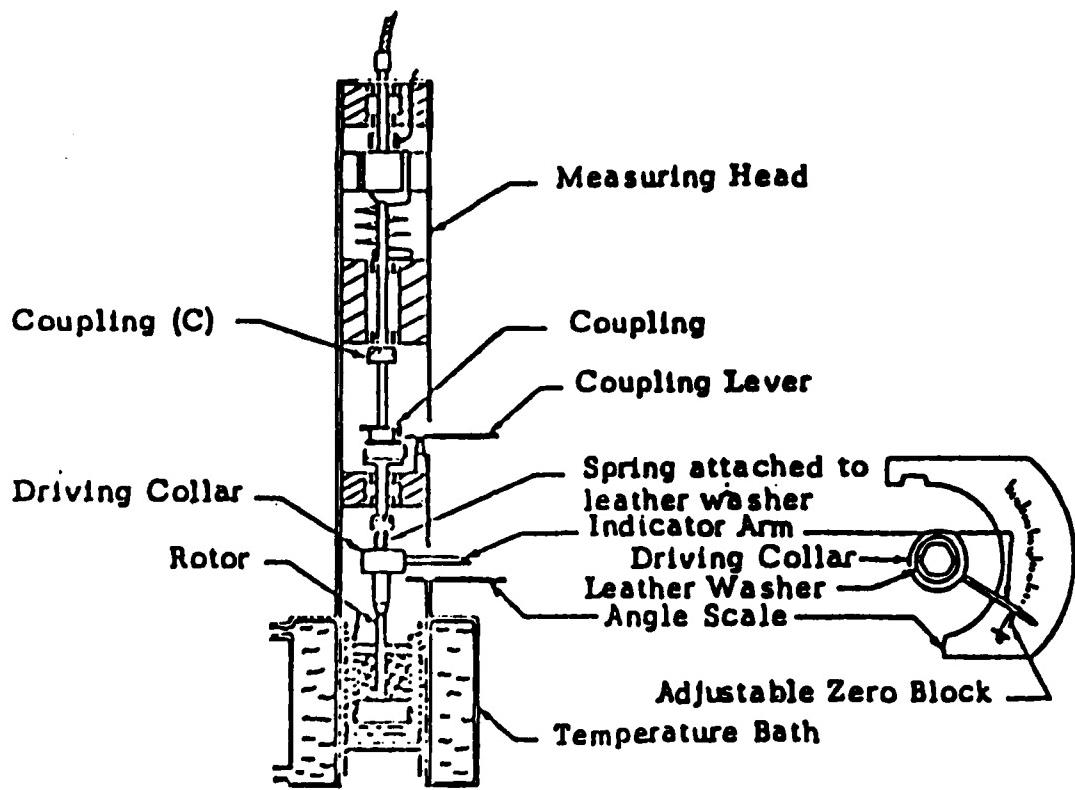
FIGURE 10-20.   ROTOVISCO WITH EIZ VISCO-ELASTIC ATTACHMENT

Torsion Bar

Torsional Displacement
(Tangential Shear Output)

Liquid

Cone

Driver Plate

Rotational/Oscillatory
Drive

Thrust on Plate
(Normal Force)
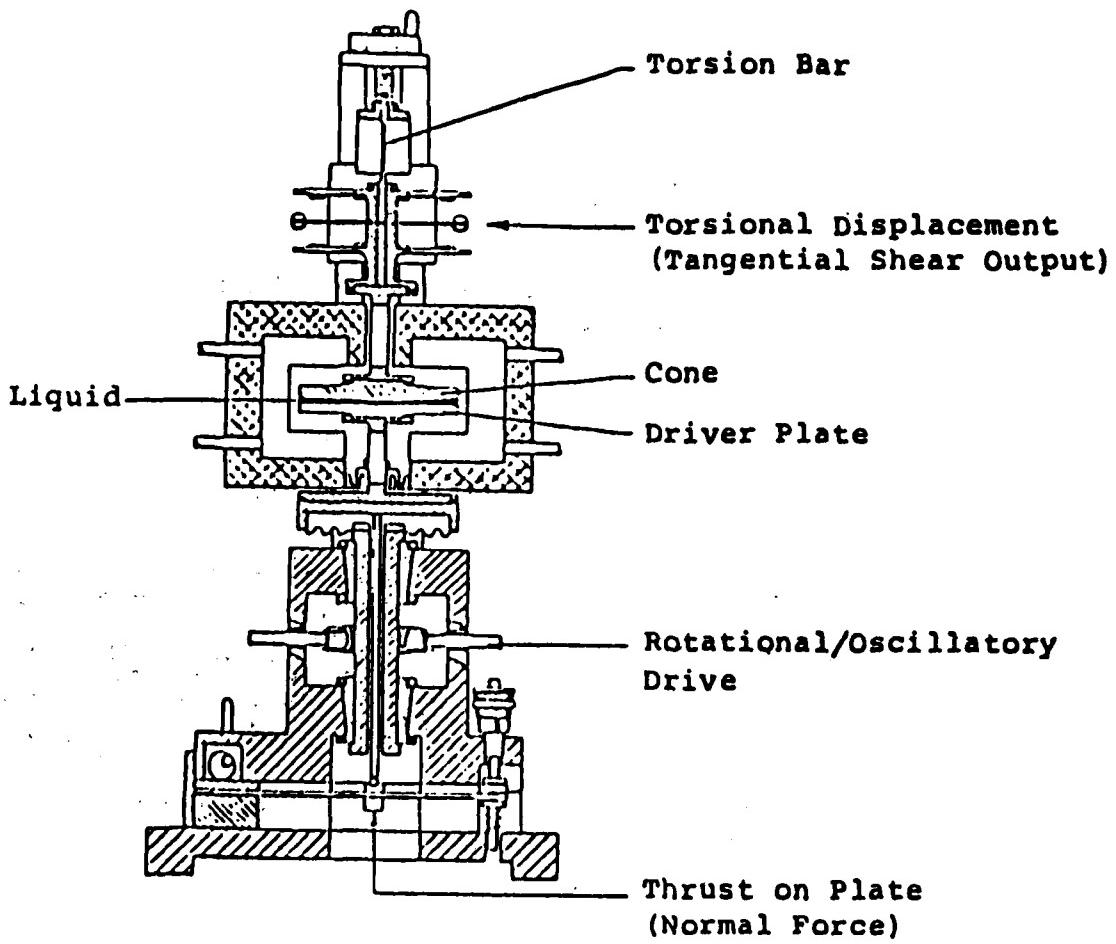
FIGURE 10-21.   RHEOGONIOMETER (REFINED WEISSENBERG DESIGN)

FILTRATION/SCREEN/
POROUS SOLID

CONVERGING FLOW

PENDANT DROP

OPEN-SIPHON
(FANO FLOW)
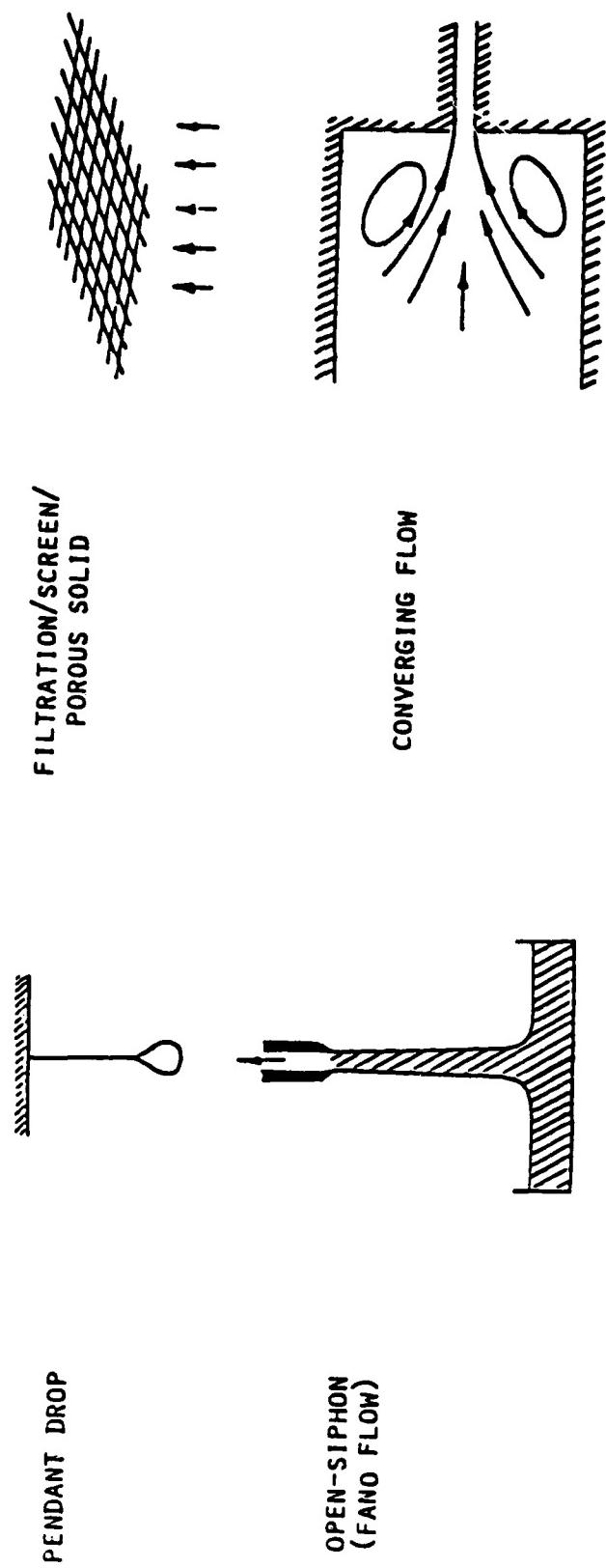
FIGURE 10-22. VISCOMETER/RHEOMETER SCHEMES ELONGATIONAL FLOW

KC/DC-10 FUEL SYSTEM SIMULATOR
By
A. T. Peacock

Staff Engineer
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California

INTRODUCTION

The DC-10 is a modern wide-bodied aircraft featuring fuel system design concepts that are now found in most commercial transport aircraft. Its fuel system is therefore characteristic of contemporary aircraft in many ways. The DC-10 is the basis for the USAF KC-10 advanced tanker/cargo aircraft. This new U.S. Air Force tanker features an inflight refueling delivery rate capability that is higher than previous tankers. This paper briefly describes the DC-10 and KC-10 fuel systems and will show how these fuel systems are simulated for test with full-scale installations in the Douglas laboratory. High shear rate areas and functions of the fuel system which depend on fuel properties will be highlighted.

THE FUEL SYSTEM

The fuel system is made up of many systems which hold, manage, control, and measure the fuel aboard the aircraft (Figure 1). Figure 2 shows the basic tankage layout of the airplane. Three main tanks are used, one for each of the three engines. Longer-range aircraft have auxiliary tankage in the center-wing area. The KC-10 has additional storage capability for off-load fuel, both forward and aft of the wing, in what are normally cargo holds below the main cabin floor. Fuel used for flight from the auxiliary tanks or from the off-load tanks is transferred to the main tanks before being fed to the engine.

GROUND REFUELING

The refueling system is shown in schematic form in Figure 3. Ground hoses are attached to the fill receptacles, the fuel load is selected, and the fill valves for all tanks to be filled are opened. Modern aircraft receive fuel at very high rates so that the servicing time is held to a minimum. The more time an airplane spends on the ground, the less time it can spend in the air earning money for its operator.

Figure 4 is a photo of the simulation of the airplane fill system. The heavy lines represent the fuel tank boundaries. The vent lines are also shown in this photo. The left refueling adapters are located at the left side fill point. These devices are held open mechanically by the nozzle. The fill and vent lines shown are production parts and are installed in exactly the same orientation as on the airplane.

TANKAGE   **TRANSFER**

VENT   **FILL**

FUEL SYSTEM

SCAVENGING   **DUMP**

FEED   **QUANTITY INDICATION**
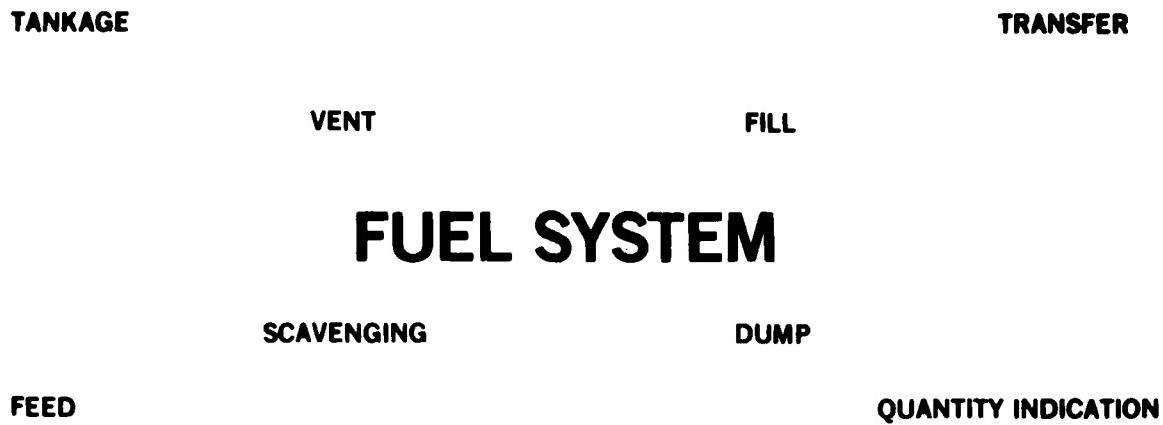
FIGURE 11-1.   FUEL SUBSYSTEMS

APPROXIMATE CAPACITY (6.7 LB/U.S. GAL)
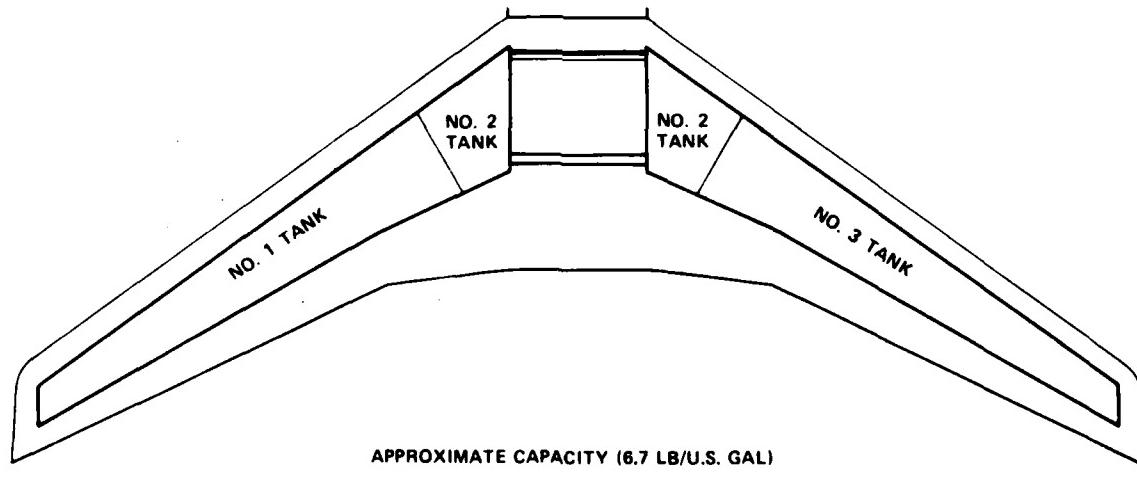
TANK	U.S. GAL	LB	KG
1	5,985	40,100	18,200
2	9,700	65,000	29,500
3	5,985	40,100	18,200
TOTALS	21,670	145,200	65,900

FIGURE 11-2.   FUEL TANKAGE — SERIES 10

FULL-LEVEL PILOT SHUTOFF VALVE (TYPICAL)

CROSS-SHIP MANIFOLD

FUELING ADAPTERS (4 PLACES)

MANIFOLD DRAIN VALVE (2 PLACES)

SURGE RELIEF VALVES (2 PLACES)

NO. 2

NO. 1

EXTENDED RANGE

SUMP DRAIN VALVE, TYPICAL

NO. 3

FILL CONTROL VALVE (4 PLACES)

REFUELING CONTROL PANEL (RH SIDE)
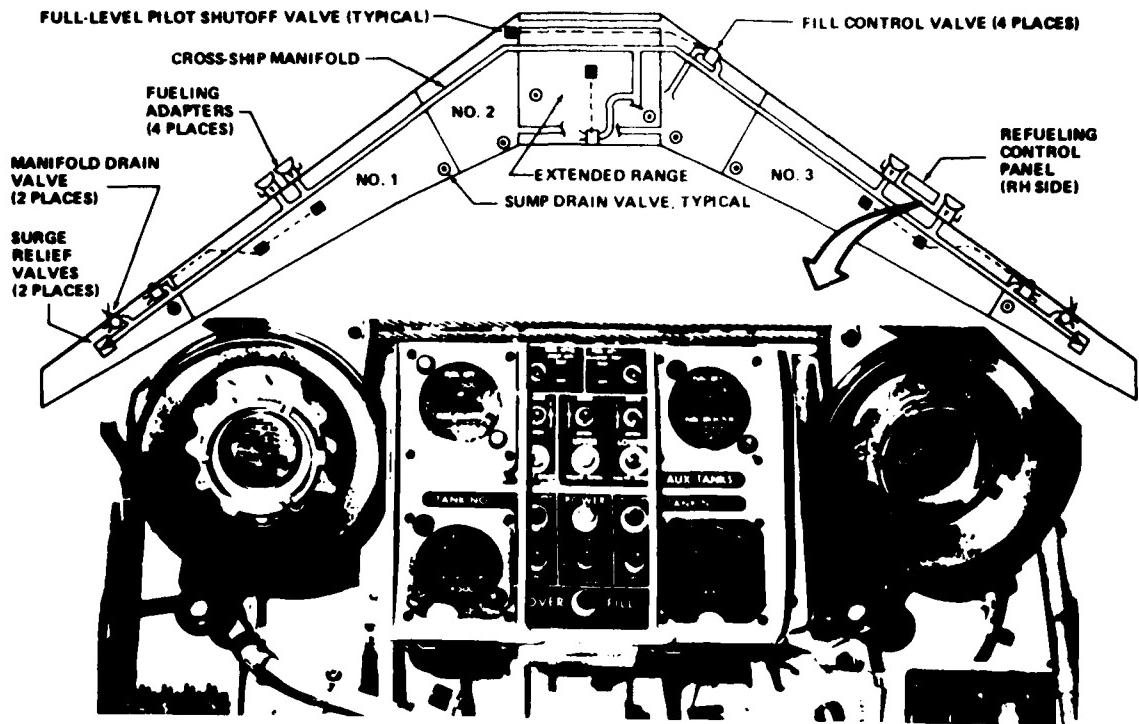
FIGURE 11-3.   FUELING/DEFUELING SYSTEM
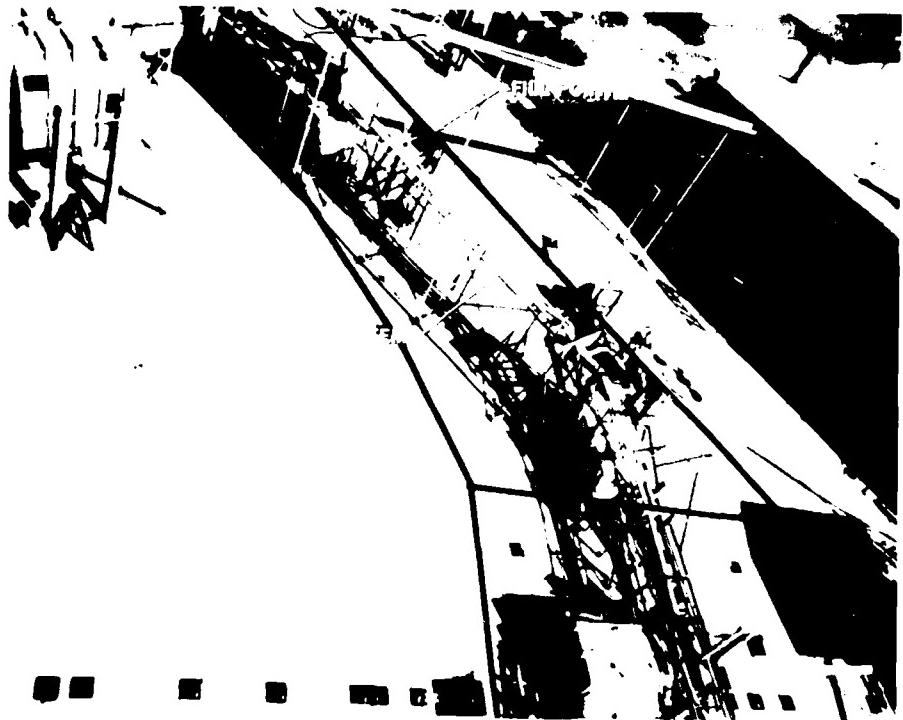
FIGURE 11-4.   FILL AND VENT SIMULATION - LEFT SIDE PLANVIEW

Refueling flow into the tanks passes through the fill valve which is regulated by its controller. Figure 5 shows a cross section of the valve and controller. Fuel pressure is ported behind the diaphragm in the controller where it works against the fill valve spring to open the valve. The amount of flow area available to fuel passing through the valve is a function of the pressure available at the valve inlet until the valve opens completely. This action will result in a relatively constant shear on the fuel until about 300 gpm, at which flow the valve is fully open. Further flow increases will result in additional fuel shearing. These shear rates are expected to be relatively low. Their effect on the antimisting qualities in newly loaded fuel can be examined in the test rig.

When the desired tank fuel level is reached, the diaphragm pressure is bled off either by opening the fill valve switch solenoid, A in Figure 5, or by opening the pilot float valves. It is apparent that operation of the fill valve is affected by the properties of the fuel being used. Higher than normal fluid viscosity will cause the valve operation to be sluggish. At high fill rates, the maximum allowable tank fuel level may be exceeded because the fuel level in the tank will continue to rise during the additional time it takes to close the fill valve. The effect of an antimisting kerosene (AMK) on this function of the system can be investigated in the test setup.

THE VENT SYSTEM

The airplane vent system is shown in Figure 6. This system is provided to equalize internal tank pressures with ambient pressures. If the fill valve system fails, fuel will flow overboard through the vent system. In some aircraft, the vent system is sized to maintain tank pressures below structural limits in case of overfill. The DC-10 has additional overpressure protection built into
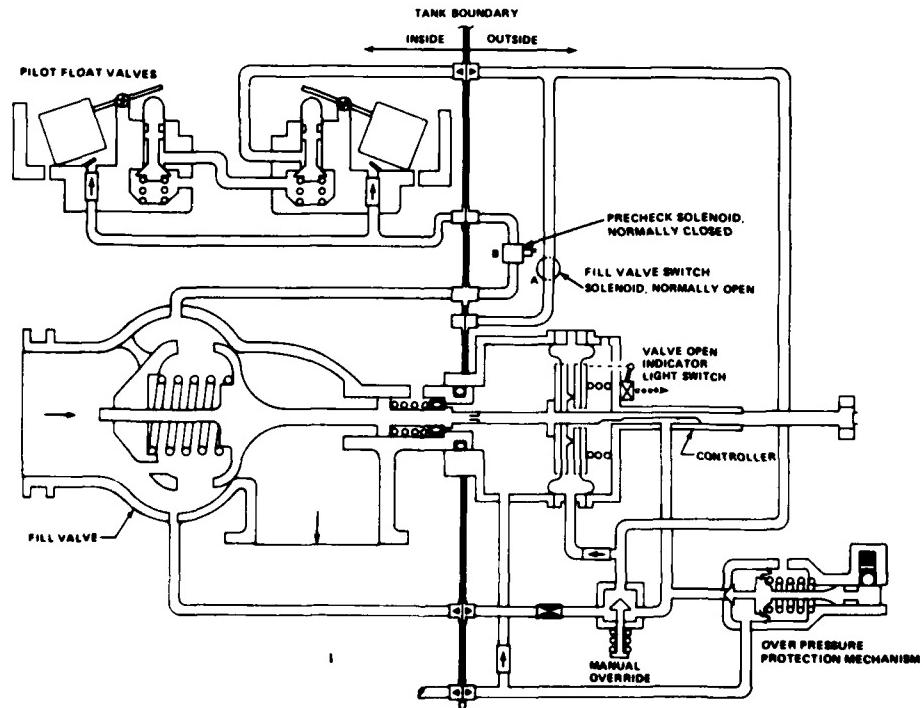

FIGURE 11-5.   REFUELING VALVE ASSEMBLY

11-4

CLIMB VENT

SEE OTHER VIEW

NO. 3 TANK
VENT
MANIFOLD
UPPER
COMPT

VENT BOX
DRAIN VALVE
(2 PLACES)

VENT BOX

CLIMB VENT

VENT BOX
FUEL DRAIN

UPPER FLAME
TANK ARRESTOR

WING BOX

UPPER
TANK

VACUUM
RELIEF
VALVE

FILL & VENT LINE

LOWER TANK

PRESSURE
RELIEF
VENT VALVE

CENTER WING AUXILIARY TANKS
LOWER TANK
DRAIN VALVE

OVERBOARD VENT OUTLET

VENT FLOAT VALVE
OVERBOARD VENT OUTLET
OPEN VENT OUTLET
SUMP DRAIN VALVE
BULKHEAD WITH CHECK VALVES
MANIFOLD DRAIN CHECK VALVE (LOW POINTS IN SYSTEM)
OVERFILL RELIEF VENT VALVE
OVERFLOW CHECK VALVE

FIGURE 11-6.   FUEL VENT SYSTEM

the fill valve controller. The use of an AMK may affect this capability. Figure 7 shows a plan view of the vent line test setup in the center wing and No. 2 main tank area. The heavy lines indicate tank boundaries.

ENGINE FEED

The engine feed system is shown in Figure 8 in schematic form. This system delivers the required amount of fuel from a tank to its respective engine at the required pressure. Self-priming, fuel-cooled, electric motor-driven centrifuged pumps are provided in case adequate engine inlet pressure cannot be maintained and to provide a motive flow for the jet pump systems. The electric pump flow rate capabilities are far in excess of single-engine flow rates because they are also designed to perform other functions in the system, such as defueling, jettisoning, and crossfeeding to another engine.

Suction feed capability — i.e., fuel delivery by virtue of engine fuel pump suction — is provided in the DC-10 fuel system. Increased pressure drop due to a higher fuel viscosity with AMK may affect performance of the engine feed system. These effects can be checked against neat fuel performance in the simulation of the No. 1 engine fuel feed system. An actual engine fuel pump, filter, and control can be used to provide data on how an AMK fuel degrades on its way to the combustor.

Figure 9 shows the General Electric CF6-50 engine fuel system. The sequence of components in the flow system is of importance. The heat exchanger provides fuel heating to prevent filter icing and engine oil cooling. Heat exchanger performance with an AMK is expected to be dif-

11-5
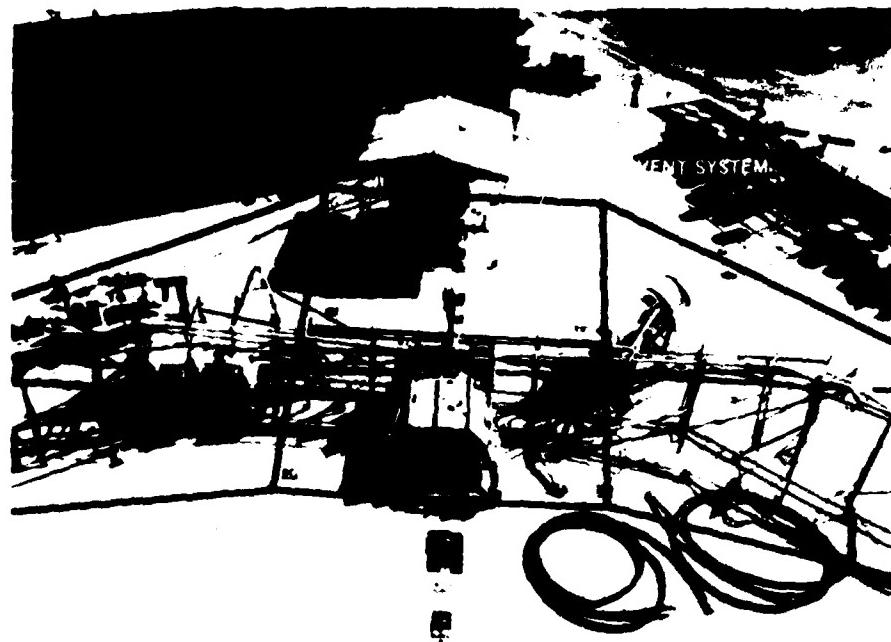
FIGURE 11-7.   CENTER WING VENT SIMULATION PLAN VIEW

AIRCRAFT TANKAGE SHOWN FOR REFERENCE

NO. 2 TANK LEFT COMP

NO. 1 ENG INLET

LEFT FORWARD
TEST TANK

NO. 1 TANK

NO. 2 TANK RIGHT COMP

NO. 3 ENG INLET

NO. 3 TANK

LEFT TEST TANK

RIGHT TEST TANK

APU INLET
NO. 2 ENG INLET
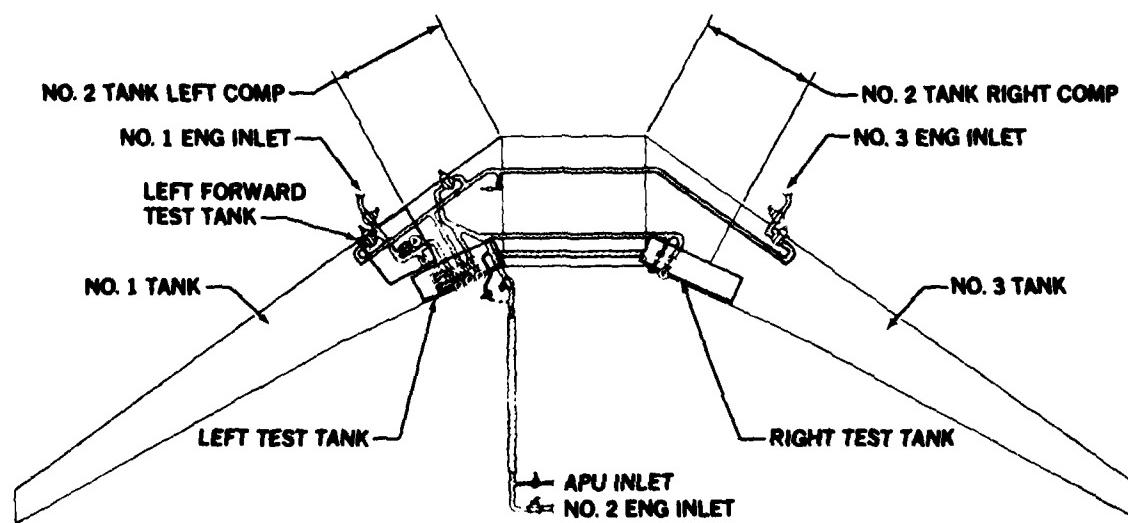
FIGURE 11-8.   DC-10 FUEL FEED SYSTEM SIMULATOR
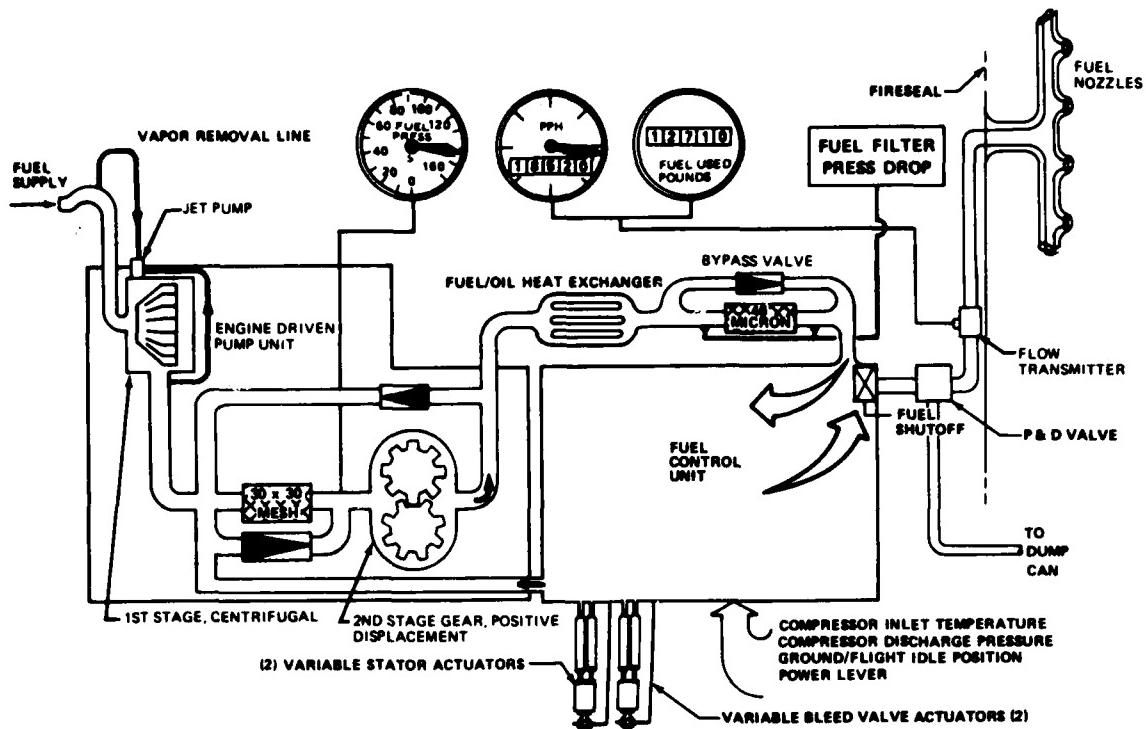
FIGURE 11-9.   CF6-50C FUEL SYSTEM

ferent than performance with neat fuel. Further, heat exchanger performance should vary with the amount of AMK degradation. Test facilities are available for examining overall heat exchanger performance at various fuel flow rates and temperatures.

INTRATANK FUEL MANAGEMENT

The effectiveness of the AMK concept is dependent on maintaining the antimisting quality of the fuel in the tanks. Systems are installed in the fuel tanks to transfer fuel, to schedule fuel transfer, and to provide continuous scavenging of water from the tanks. These systems use fuel from the engine feed line which has already been through the tank fuel pumps. The pump cooling flow is returned to the tank after having been sheared by the impeller and having passed over the electric motor windings. All of these actions affect the fuel's antimisting quality.

The fuel in the No. 1 main tank is used in a special sequence. Figure 10 is an elevation view of the tank. The fuel is used in the order shown by the Roman numerals. The sequencing of the fuel is very important to the overall weight and balance of the airplane, the drag of the airplane, and therefore to the operating efficiency and profitability of the airplane.

Figure 11 shows the intratank transfer and automatic scheduling system for the No. 1 fuel tank. At nose-up attitudes, the jet pump system transfers fuel from the outboard compartment to the inboard part of the tank near the electric pumps. At more normal attitudes, this fuel is transferred by gravity.

ELEVATION VIEW

INBOARD COMPARTMENT

OUTBOARD
COMPARTMENT

5000 LB
CONTROL LEVEL
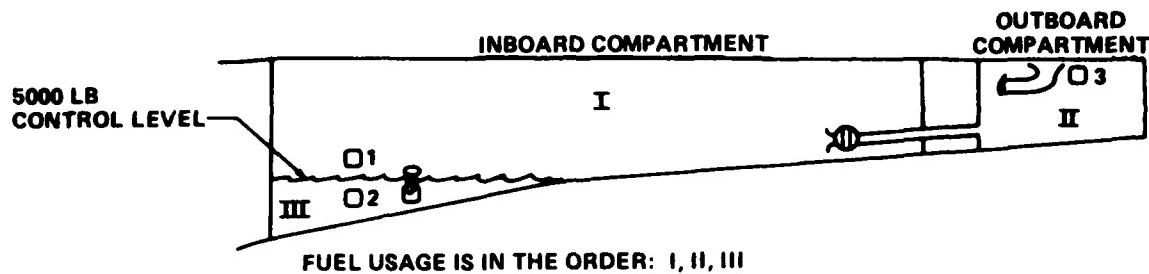
FUEL USAGE IS IN THE ORDER: I, II, III

FLOAT SWITCHES CONNECT THROUGH LOGIC CIRCUIT TO ILLUMINATE
FUEL SCHEDULE LIGHT WHEN:

(A)   OUTBOARD COMPARTMENT LOW OR DRAINING EARLY (FUEL ABOVE
      SWITCH 1 AND BELOW SWITCH 3) OR

(B)   OUTBOARD COMPARTMENT FULL BEYOND SCHEDULED START OF
      DRAINING (FUEL BELOW SWITCH 2 AND ABOVE SWITCH 3)

FIGURE 11-10.   OUTBOARD MAIN FUEL TANK — FUEL USAGE SCHEDULE

TO ENG
#3

CHECK
BULKHEAD

TO ENG
#2

◻ JET PUMP
◻ PRESSURE ACTUATED VALVE
◻ CHECK VALVE
◻ TRANSFER FLOAT VALVE
◻ BOOST PUMP, AC
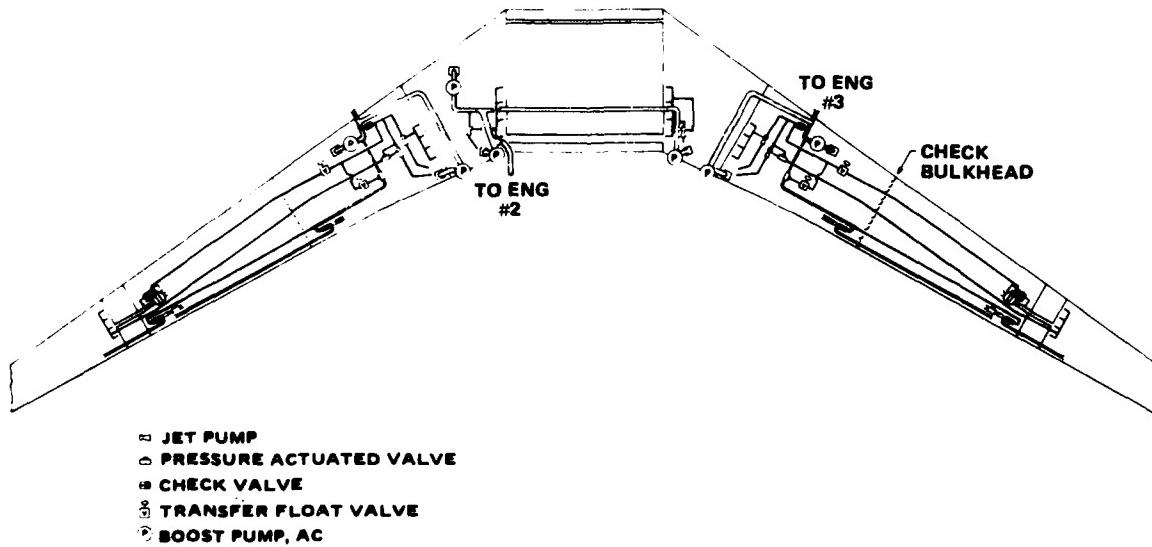
FIGURE 11-11.   FUEL TRANSFER AND CONTINUOUS SCAVENGE SYSTEM

11-8

The gravity transfer flow is controlled by the system shown in Figure 12. The float valve at the inboard end of the tank maintains the fuel at a prescribed level. When the inboard fuel level is above the float, pressurized fuel from the feed line can flow outboard to close the gravity drain valve and to make up for fuel being transferred inboard by the continuous scavenge system. When the float is uncovered, makeup flow stops and the gravity drain valve opens as fuel pressure behind the valve diaphragm is relieved. The speed of this action is clearly dependent on fluid properties. Excessive swings in inboard fuel level will give the crew a momentary indication of system failure and will result in blinking cockpit warning lights. Obviously, the function of this system should be examined when considering operations with an AMK.

The photograph of the fuel feed system test rig in Figure 13 shows the huge structure supporting the fuel feed system simulation. This fixture was built for certification and development testing of the fuel feed systems. The size of this test fixture is due to the length of the system being simulated, the amount of fuel supported during the test, and the ability to tilt the rig to simulate airplane pitch altitudes. Full altitude and limited temperature capabilities are available. Figure 14 is a photograph of some of the tankage available on the feed rig platform.

This facility can be used to compare the performance of an AMK with neat fuel. There is sufficient tankage available that short flight cycles using AMK can be simulated. The fuel used in the test can be scheduled through the tankage in such a manner that the effect and history of repeated simulated flight cycles on reserve fuel antimisting quality can be examined. Fuel samples can be extracted at various times during a series of flight cycles and tested using the latest methods of measurement for fuel quality. Correlation of these measurements with the results from the FAA wind shear tests can indicate the compatibility cí an AMK with an unmodified system, or system modifications to maintain tank fuel quality can be evaluated.
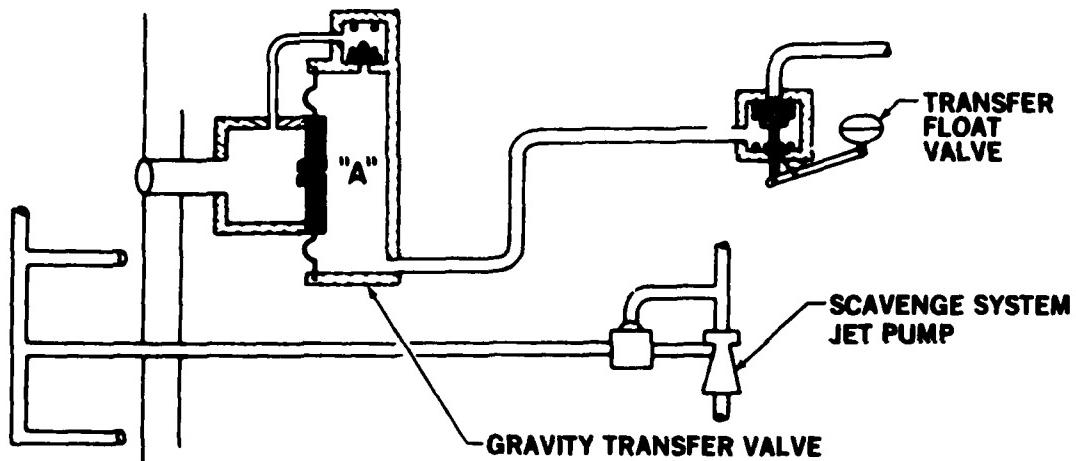
FIGURE 11-12.   OUTBOARD COMPARTMENT GRAVITY TRANSFER AND SCAVENGE SYSTEMS
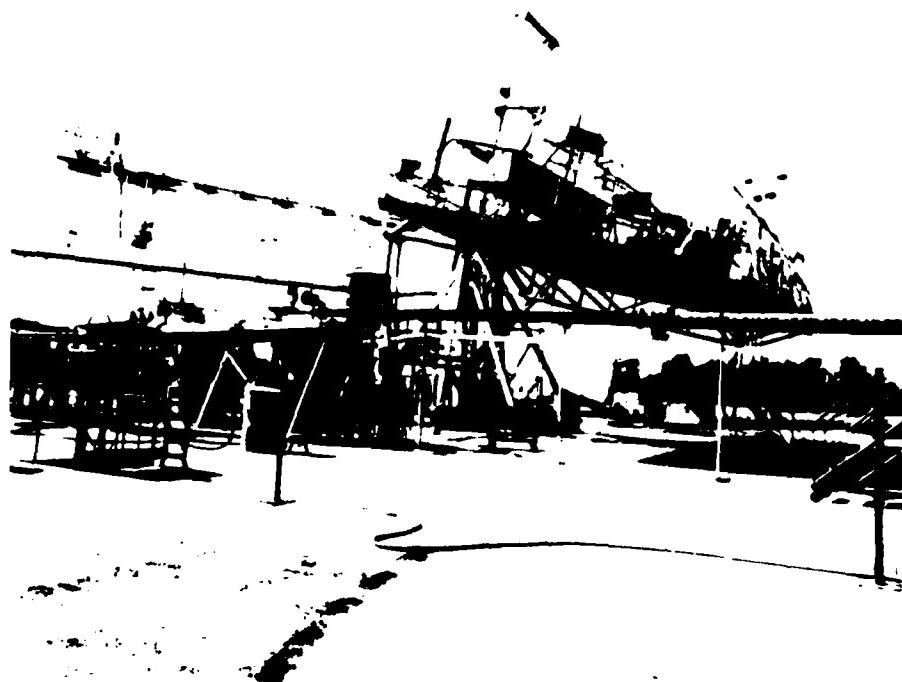
FIGURE 11-13.   FUEL FEED SIMULATOR TEST FIXTURE

FIGURE 11-14.   LEFT FEED TEST TANK

11-10

THE KC-10

A schematic of the KC-10 fuel system is shown in Figure 15. This system is essentially the DC-10-30 long-range airplane system with the addition of tanks, hydraulically driven off-load pumps, and the capability to receive or to deliver fuel inflight. A hose reel is provided for probe and drogue refueling. A flying boom conducts fuel through a nozzle to the receptacle-equipped aircraft.

The complete full-scale inflight refueling system is simulated in the Douglas laboratory. The boom nozzle is installed in a UARRSI receptacle. The photographs in Figures 16 and 17 show this installation. This setup can be used to examine the effect of an AMK (additized JP-8) on off-load flow rate capability. The effluent flow from the test can be checked for the maintenance of antimisting quality in fuel delivered to the manifold of a receiver aircraft. The maintenance of fuel quality in the receiver aircraft, however, will be determined by that aircraft's system characteristics. Figure 18 is a photograph of the KC-10 Extender.

SUMMARY

To summarize, the full-scale simulation of a modern wide-bodied aircraft fuel system can be used to examine the compatibility of any candidate antimisting kerosene with an aircraft fuel system which is characteristic of contemporary commercial and large military aircraft. The effects of the system or of modifications to the system on the quality of an AMK being used can be evaluated.
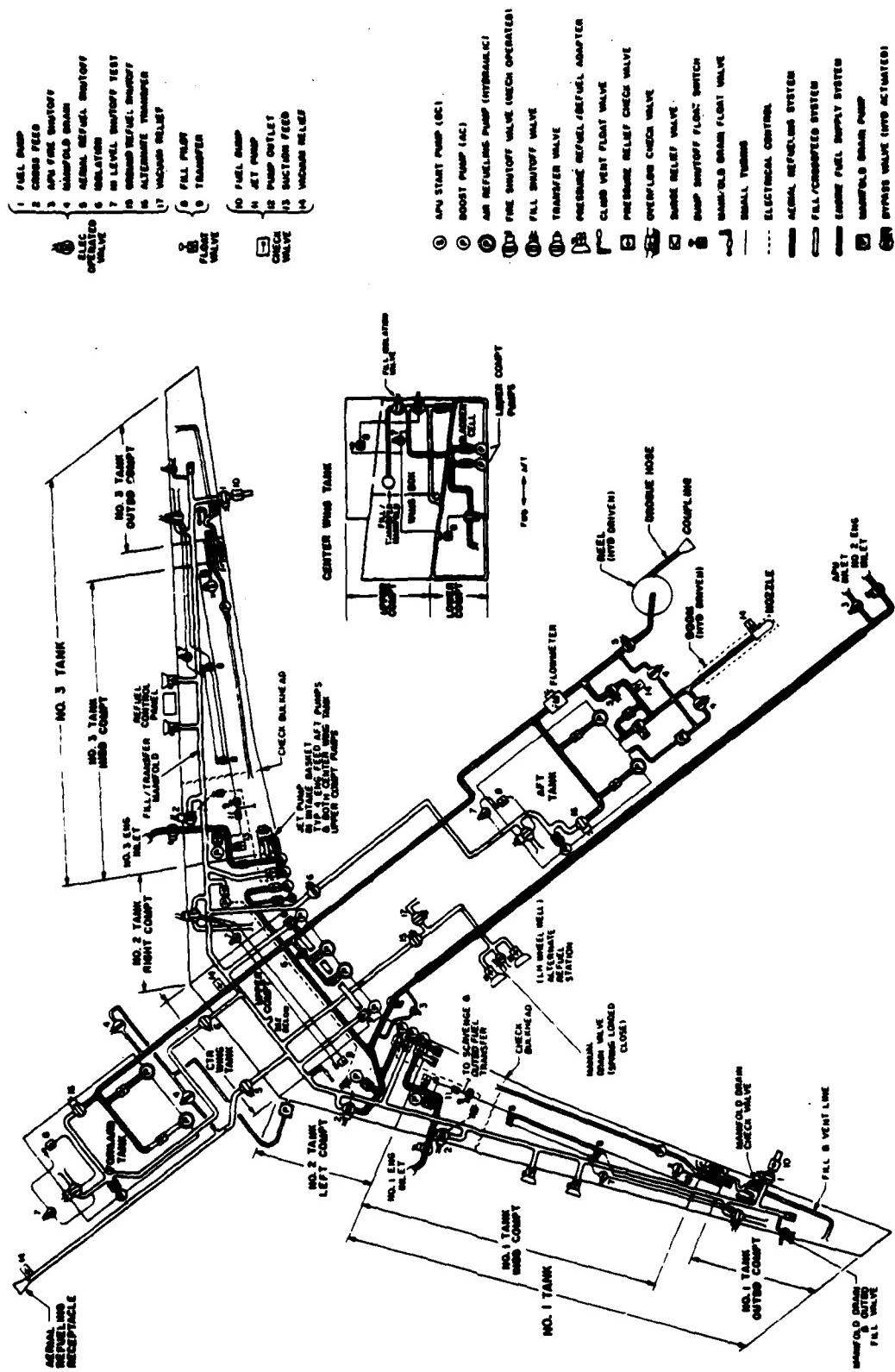
FIGURE 11-15.   KC-10 FUEL SYSTEM
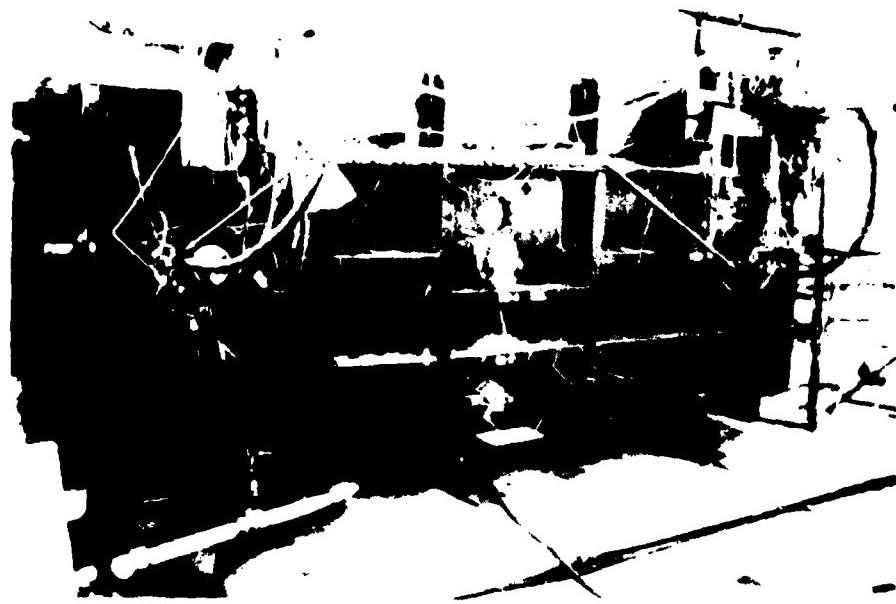
FIGURE 11-16.   AFT TANK AERIAL REFUELING PUMPS
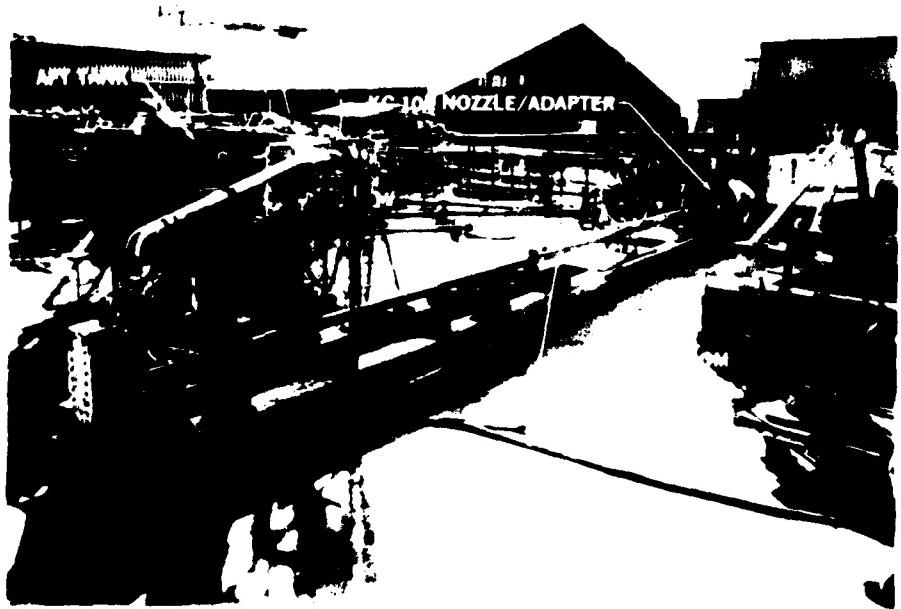
FIGURE 11-17.   BOOM TEST SIMULATOR

FIGURE 11-18. KC-10 EXTENDER

Questions and answers following "KC/DC-10 Fuel System Simulator"

Discussions:

Mr. Curran: Tom Curran FAA, Seattle, Washington. Neither in this presentation nor the program overview yesterday was there any discussion of looking at the certific-ability of the aircraft as modified or without modifications during the feasibility studies. I'm suggesting that the FAR 25 rules which affect the fuel system and the isolation requirements for our protection, etc., should be considered in the feasibility studies.

Mr. Westfield: Our intent is to prepare the data base that the FAA regulatory people will use to initiate any rulemaking action. We won't do it here.

Mr. Grill: TRW. Have you considered the possibility of nonoperative booster pumps, nonoperative jet pumps?

Mr. Peacock: Yes, we have considered that. We will be examining the suction feel capability when there is no electric power available for tank booster pumps. As far as the jet pump being inoperative, if you were to go into a booster pump-out situation and maintain high aircraft altitude for an extended duration of time under low fuel conditions, you would probably have to put the nose down a bit once in a while to make sure that you have gravity transfer. Actually, that's no different than the current airplane.

Mr. Peat: Peat, Rolls Royce. Tom, have you considered how you are going to approach the fact that if your samples are standing around a long time before you submit them to laboratory-type testing, that they may not represent what the condition of the fuel was at the time you isolated it through one of your sections?

Mr. Peacock: Anybody who has been using the fuel, receives it from ICI in Wilming-ton on a premixed basis. In our case, it will be trucked from ICI Wilmington, Delaware to Long Beach, California for use. It will come in several batches because we don't have the capacity to store all the fuel that is required. This is a once through test. We don't have the capability of having recirculating flows, so we can't just order up a couple or three thousand gallons and do every-thing. We've got to get a lot of fuel in order to have a representative test. As far as sampling is concerned, we do not have the facilities at our plant to do that sort of work. However, JPL is very close and any samples that we take will be evaluated at JPL. We have a coordinating setup with JPL to provide evaluation of samples in the minimum time possible.

Mr. I. Thomas: Boeing Company. If this program is going to look at the effect of the booster pumps degrading the reserve fuel, what happens when you add the fresh fuel or the situation where the booster pump or the APU is run on the ground and you can have the booster pump circulating fuel in the tank for cooling for quite extended periods of time? Presumably, this will be degrading the fuel. Are you going to look at that kind of activity?

Mr. Peacock: Yes and no. Yes to the first half; no the second half. In the currently defined program we will be running repeated tests which are flight cycle simulations. We can schedule the fuel these tanks so that it looks like a short flight. We don't have the capabilities to simulate a 9-hour flight or anything

like that, but we do intend to run about an hour and a half roughly per flight cycle for repeats of the cycle where you fuel up at the start, use the fuel and reserve a quantity, come back, refuel again, and go through that cycle four times.

PANEL DISCUSSION

INTRODUCTORY REMARKS

Dr. Reichenbach: Good afternoon. I would like to start out by stating that the primary purpose of this forum is to encourage an open discussion of what has been going on here for the last couple of days, and what we should be doing in the future. I'm substituting for Mr. Albrecht, the Associate Engineer for Engineering Development, who has the responsibility for R&D efforts in aircraft safety. As Mr. Del Balzo stated yesterday, the AMK Program has a very high priority in the FAA list of items to be accomplished. We believe the program presented the last day and a half is a very comprehensive program, but we recognize that industry and public viewpoints can ferret out approaches and problems that may have escaped the technical approaches discussed here. We are, therefore, concluding the detailed presentations with this panel discussion. We hope that the questions posed to our panel later are of the types that will stimulate discussion. Input and comments from the audience are welcome. The panel discussion has been structured in the following way. First, each panel member will give a short discussion concerning his inputs and feelings concerning antimisting fuel. At the conclusion of the separate statements, other members of the panel may comment, if they wish. I will then entertain discussion from the floor as time permits.

E.F. Versaw, Lockheed-California

The aircraft industry is continually searching for ways to improve the safety of aircraft, including fire safety, which is the primary concern of this conference.

I am sure that certain people in the FAA have the impression that industry is resisting safety proposals primarily on the basis that they require costly design modifications. However, I want to assure you that, second only to passengers, the aircraft industry has much to lose by ignoring these proposals. Competition between airlines and with other modes of transportation to win the travellers support, creates the greatest incentive we can have to improve the safety of our airplanes. I might add, most of us are also passengers, giving us a dual reason for wanting to make flying safer.

The entire industry is conducting research and participating in many safety programs. New concepts are investigated and, if they prove to be more effective than existing designs after a thorough and often costly evaluation, are incorporated in our airplanes as soon as possible.

At the present time, antimisting kerosene seems to offer the greatest potential for a significant improvement in aircraft fire safety. We are concerned that the development program for AMK will be orderly and complete. Production problems must be resolved and feasible blending techniques must be developed.

The adverse impact on fuel handling operations has to be minimized or eliminated. Those problems have yet to be examined. The impact on the aircraft, the engine, and operating problems in-flight must be acceptable; and, of course, the results of any cost-benefit studies must be evaluated. The impact of each investigator's findings on those of other investigators must be examined and acted upon if a new direction to the program is indicated. That brings to mind one more factor that bothers me, and that is the apparent urgency by the FAA to issue a Notice of Proposed Rule Making (NPRM). Although I feel that the developmental investigations should be accelerated, it might be more appropriate to wait until major problems are resolved before scheduling the NPRM.

As a final point, it concerns me that most of the constructive comments at this conference seem to come from the United Kingdom participants. It is my feeling that the dissemination of information on the AMK Program is not as thorough and complete in the United States as it has been in England. Why that is I don't know; but I would like to see a change. I would like to read a recommendation that the SAFER Committee put forth in its final report.

"Recognizing that SAFER Committee's efforts are only a beginning in focusing the technical and regulatory attention necessary for rational aircraft fire safety improvement, the Committee further recommends that FAA move rapidly to establish a standing technical advisory committee structure in the manner of the highly successful NASA Research and Technology Advisory Committee and the Air Force Scientific Advisory Board. Such a body would provide regular and frequent specialist advice, over a long term, to the FAA aircraft fire and explosion research program."

This recommendation of the SAFER Committee, if acted upon, would help to coordinate the various activities in the program, and ensure that interested organizations in the United States could contribute their expertise towards the expeditious resolution of existing problems. Thank you.

Thomas G. Horeff, FAA Propulsion Branch, AWS-140

In Mr. Luffsey's keynote address yesterday morning, he stated that the FAA had estimated that about 30 percent of the fatalities in impact-survivable accidents are caused by fire or the effects of fire; and I want to emphasize that those fatalities occurred in impact-survivable accidents which are relevant to the antimisting fuel concept.

These data were drawn from accidents between 1964 and 1978, in which period there were 31 impact-survivable accidents in which fatalities and post crash fire occurred to U.S. air carrier turbine powered aircraft. As Mr. Sokolsky mentioned yesterday, data on causes of fatalities, particularly with respect to fire or the effects of fire, are very hard to obtain. So these data that I am going to recite are based partly on the accident data where the NTSB did, in fact, make findings as to the cause of fatalities and also on those accidents where the NTSB did not make the findings, in which case the FAA estimated, based on a variety of criteria, the number of fatalities due to fire.

"In 18 of 31 accidents, fuel was released upon either complete wing separation or partial wing separation following impact. In these 18 wing accidents, there was a total of 831 fatalities of which about 300 were estimated due to fire. In 10 other accidents, fuel was released from damaged fuel tanks. In these 10 accidents, there were 600 total fatalities in which about 200 were estimated due to fire."

Therefore, in rough terms, about a third of the fatalities were found to be or estimated to be due to fire or its effects. So we see that in these antimisting fuel relevant accidents, there is nothing on the horizon that might be looked at to solve the external fire problem except something that can be done to the fuel. It has been established that, for example, crash resistant tanks in the integral wing tanks of transport airplanes are not feasible. So we are looking at something then that seems to be the only answer to reducing this factor of one-third of the fatalities due to fire in impact-survivable accidents.

This was reiterated in a 1977 public hearing held in Washington on Fuel System Fire Safety, where the AMK program received recommendations for rapid progress and, as Ed Versaw just indicated, the SAFER Committee, which concluded its operation last June, felt that if successful, AMK could provide the single most significant safety improvement to reduce the postcrash fire hazard. The SAFER Committee also supported the 1984 target date for the data base to initiate rulemaking procedures. It also indicated that AMK could possibly be operational within 10 years.

If this, in fact, is possible, it leads one to suggest that AMK should certainly be looked at and evaluated for compatibility with the turbine fuels that are likely to exist in the time frame 10 years from now. Overall, with respect to the AMK program, I would like to refer to the qestion that Frank Taylor asked yesterday concerning consideration of acidents due to AMK. That particular question highlights the fact that AMK must be shown not to degrade the current level of in-flight reliability that we enjoy today; such that there will not be any decrease due to AMK which is being proposed to solve a postcrash fire problem.

The NPRM that is scheduled for preparation in mid-1984, will be based on a final cost benefit analysis prepared by Mr. Sokolsky and his group using the procedures and logic that he described yesterday. The analysis will be used initially to,

more or less, generate ballpark figures. Over the next 2 or 3 years, these ballpark figures will be refined, based on the results of work such as Tom Peacock outlined on the modifications necessary in a DC-10 fuel system and other work done by engine manufacturers, and so on.

I want to emphasize that the initial cost benefit studies that are being done will provide just ballpark figures to give us an idea as to whether it is proper to proceed with the program. The NPRM is going to be coordinated with the Transport Airplane Certification Lead Region, which is the Northwest Region stationed at Seattle and with the Engine Certification Lead Region in Boston, and it must be international in nature and, therefore, will be discussed through the International Civil Aviation Organization and with foreign airworthiness authorities. It is possible, in view of the large costs that are envisioned to implement the use of AMK, that a request to Congress to provide funds to reimburse the costs of recertification of engines and aircraft may be undertaken.

I noticed several gentlemen in the audience; some from Sikorsky Aircraft and a gentleman from Westland, and I feel that we must apologize, since we are really not giving the helicopter operating environment its due respect here in this conference. So, I would like to discuss a little bit about helicopters. First of all, to provide some very general data with respect to helicopter accidents, and while these particular data I am looking at are data between 1964 and 1969, it was indicated that 30 percent of the major accidents involving major structural damage did involve fire and that 45 percent of those fire accidents were fatal compared to 28 percent of the non-fire accidents.

Going back in time then, to 1970-1971 in particular, when the U.S. Army was looking at means to improve the helicopter postcrash fire accident problem in Viet Nam, the Army Fuels Branch at Fort Belvoir sponsored some tests at Phoenix of fuel tanks impacting under helicopter impact conditions with FM-4 and another antimisting agent referred to as AM-1. It was shown that even under helicopter impact conditions AMK does, in fact, provide similar benefits to that shown in the full-scale experiments at Lakehurst with fixed wing aircraft.

Another important consideration has to do with the insurance costs. We made a survey several years ago which indicated that helicopter insurance runs something like 25 percent of the total operating costs of helicopter operations as compared to 4 to 5 percent of the total operating costs of fixed wing aircraft. I may probably stand correction on that point, but the point I am trying to bring out is that certainly there will be less system modification necessary for helicopter fuel systems; and the fact that there may be some benefit in reducing the insurance costs, there may be a basis for initiating use on the part of some helicopter operators on AMK without regulation. I don't mean to say that in jest, because we did talk with a relatively large helicopter operator in the Gulf Coast Area and it was indicated that if AMK is shown to reduce the fire problem and eventually the insurance costs, t' s operator would voluntarily use AMK in his fleet. And now, let's consider general aviation.

I would like to refer to a General Aviation Fuels Workshop that was held at NASA-Lewis Research Center in Cleveland earlier this month where the workshop members recommended to NASA that a new reciprocating or rotary engine be developed to use turbine feul, probably a stratified charge engine, and that it be developed and technology transferred to the engine manufacturers to have such an engine produced

by 1990. So here we have, in addition to the existing turbine-powered airplanes, the potential for reciprocating powered airplanes in the 1990's time frame using turbine fuel.

So with respect to the overall AMK environment, it looks like, in addition to the NPRM that is scheduled for 1984 on turbine-powered transport aircraft, that helicopters and general aviation may be able to make use of it as well. One piece of data that was not brought out in the discussions had to do with the additional benefit of AMK in the area of electrical conductivity. Back in the mid-70's, we issued samples to the Naval Research Laboratory and they ran some electrical conductivity tests on jet A which happened to be 1.8 conductivity units, and on 0.3 percent FM-4, it was measured to be 326 conductivity units which is the recommended range for conductivity to reduce the static electricity hazard. Thank you.

Discussions: Mr. Thomas, ATA. I would like to make two observations and ask a question. My first observation is that I am not going to get in an argument again. By accident statistics, Tom, I would recommend section 1 of the SAFER Committee Report, the Aircraft Postcrash Fire Problem Definition, for everyone to read. The second observation is on your comment on insurance. That question arose in 1974 when Notice 74-16 came out and insurance companies were contacted at that time and they said: "In no way are we going to reduce the insurance costs because you add something to your airplane until we find out from about 10 years experience whether it has done any good or not." Those are the two observations. The question is: In listening to what has gone on here for the past couple of days, I can come up with a couple of scenarios for the NPRM. One scenario says: The FAA proposes to require the use of a proprietary product for our airplanes and the use of a proprietary blending method." That's one scenario. I don't think FAA intends that, but I'm just curious as to how that's going to be worked out; and secondly, the FAA intends to issue an objective rulemaking rather than a subject rulemaking. Then, I can see a rule coming out that says: "You have to do something." In an advisory circular, coming out and saying, "One acceptable means of this is using FM-9."

What is going to happen and who is going to fund any studies that might be necessary on alternatives to FM-9?

Mr. Horeff: In response to your last comment, Ed, right now the rulemaking strategy hasn't been worked out, but standard rulemaking procedures call for, first of all, not requiring the use of proprietary products. There has to be at least two ways to achieve the desired objective, and in the rulemaking activity, the Administrator looks for what is proposed and what are alternatives to what is proposed and all this will have to be in the NPRM program.

I appreciate your comments, incidentally, about the accident statistics. I know in the SAFER Committee Report that only the NTSB data were referred to, but I do want to emphasize there were accidents where the NTSB did not make findings of fire fatalities, and that is why FAA went ahead and made estimates; and I do want to emphasize that these are both NTSB data and FAA estimated data that I'm talking about today.

Dr. Parker: John Parker, NASA AMES Research Center. I am not certain that the conclusion in all of these fire-related statistical deaths you speak of, which involve explosion are as clearly defined as you think. Fuel can be spilled. I'm not trying to generate a scenario, but how confident do you feel in your statement

that the misting and fire propagation is indeed the primary fire case in these fire deaths. Are there other ways, if that had not happened the fire would have been ignited by some other mechanism or are you perfectly certain this is one-to-one misting ignition versus fire-death relationship, irrespective of statistics?

Mr. Horeff: Well, looking at the nature of the aircraft damage, conclusions are drawn that there were copious quantities of fuel released in the dynamic phase of a survivable accident where it would be released in mist form. So as I say, these are accidents where the use of AMK may have reduced the number of fire-caused fatalities.

Dr. Parker: I don't think there's a hard model for that. I think that's a conclusion that you're making based upon a very limited model and a very limited amount of real data.

Mr. Ginn: James Ginn, FAA Technical Center. In Mr. Luffsey's keynote address he stated that since 1964 there were 17 incidents in which antimisting fuel would have played an important role to save lives. He also went on to say that 30 percent of these fatalities were due to fire. For argument's sake, let's assume that maybe 200 people died in these 17 fires for a total of 3400 lives, and times that by 30 percent or 1020 lives divided by the 17 years, comes out to 60 lives per year. I'm not sure they will stand, but based on those figures of 60 lives per year, do you think we should continue to spend far more time and money on the antimisting fuels based on 60 lives per year figure?

Mr. Horeff: The basis for expending funds is not based on an average of 60 lives per year. It's based on the overall hazard, and its relationship to the never ending quest for improving safety. I can't be any more specific. I'm sorry to have to give you a general answer like that.

David A Hartline, Transworld Airlines

The possibility of improving passenger survivability during ground crashes is really encouraging. To do so without adding another complex mechanical or electrical system to the aircraft will be most welcome. Reducing the likelihood of ignition and slowing speed of the flame/over a spill will save lives during survivable incidents. The airlines certainly support this effort. As in all things, we won't get something for nothing. Modifying engines, buying the additives, and accepting the maintenance costs of handling fuel with the additive in it may not be the only burdens. We must be sure that in solving one problem we do not introduce other problems of the same or worse magnitude. Decreased fuel quality control can have dire consequences. Interruption of fuel feed to the engines or improper combustibility of fuel in the engine cannot be tolerated. We must maintan the present reliability of our fuel handling systems from the refinery to the aircraft and from the fuel tanks to the engine. In-flight flame-outs or the inability to relight at altitude, as a consequence of the modified fuel, cannot be tolerated. As with any new additive, besides providing a new useful function, antimisting additive must also be evaluated to establish that it is compatible with jet fuel, with all other additives used in jet fuel, and with the aircraft engine, APU, ground fuel handling system, and accessory systems. Screening by the manufacturers, testing in simulated aircraft fuel systems, and flight evaluation must all precede wide-scale adoption of the additive.

Lastly, there are other unique aspects that can't be ignored. Current regulations require engines not to exceed specified maximum limits for smoke, hydrocarbons, carbon monoxide, and oxides of nitrogen. Engine specific fuel consumption is critical with present and future high energy costs. Every effort must be made to minimize increased fuel consumption which will result from the use of antimisting jet fuel. Increased TSFC has already been estimated at one-half of one percent to mechanically degrade the fuel up-stream of the engine fuel system. For U.S. airlines which are using 10 billion gallons of fuel per year, this amounts to an increase of 50 million gallons per year. The goal of increased safety during impact survivable crashes is a worthwhile objective. It is not easily attainable, but it is well worth an all-out industry effort to determine if it can be achieved. I would like to add a few additional comments based on today's discussions. One is the ever present presence of water in the fuel. We certainly have to have an additive in the fuel that can tolerate water. There is no way that we can keep small amounts of water out of fuel tanks, since condensation due to high altitude temperature change results in precipitation of water in the fuel. Also, regarding when the additive is mixed into the fuel, some statements have been made about how long it takes for equillibration to take place; i.e., until the additive is ready for its purpose and provides the safe antimisting characteristics that we want. That is something that will be critical because takeoff will commence within a half hour or less — and we would have to have an additive that would be effective during takeoff and taxi condition as well as the landing condition. The cost estimates already prepared are disturbing because the modifications required for the engines are not yet known. I realize that the people that contracted for the estimating have indicated it is preliminary data and will be revised and adjusted as they go along. We certainly agree that's needed. Hardware costs, when we get closer to them, will be something that they can tie down. We can also figure out how much aircraft out of service time and/or what opportunities we will have for access to modify engines. It would certainly appear the fuel nozzles are

going to be replaced and that would mean we would have to do this during hot
section refurbishment of the engine. This is not a period of months but a period
of years.

We're certainly encouraged by the films which showed the ability of the antimisting
fuel to prevent fire conflagration. It's surely worthwhile determining if it would
be possible for us to have that wonderful benefit.

Discussion:

Mr. Wittenberg: Air Canada.   Just a comment here, Tom Horeff indicated that the
NPRM would have a world effect on most airlines, and I think the one thing that has
not been taken into consideration is the availability of kerosene throughout the
world.   There are many countries where all airlines would not be able to use jet A.
That is right now in Canada.   The ratio amongst all airlines is about 60/40.   60
percent is kerosene; the other 40 percent is jet B and if the NPRM did not allow
the use of jet B to come into the country (U.S.A.), it would have a traumatic
effect on the airlines.

John W. Mossel, ICI Americas, Inc.

In the interest of brevity, let me not repeat some of the things I mentioned
yesterday, but let me just add to some of the comments during these 2 days which I
found very enlightening. Certainly, some of the questions and concerns that have
been raised are necessary and they have to be raised. I think the program that the
FAA is looking at is intended to do just that, to raise those questions, to look at
them to see if there are obstacles and where they may be; how we, collectively, as
industry and Government can address these issues. Certainly, we, as part of
industry, the chemical industry, are addressing this particular question of fuel
safety. I trust that other companies will address this question as well.

The ambitious schedule that has been set forth in terms of submitting alternative
candidates is rather time constrained. However, before being implemented, if it
ever gets that far, there are a number of years between now and when this will come
into being. So there's certainly sufficient time for a great many companies, a
number of them represented here, to do significant research efforts and contribute
their facilities to this whole area of antimisting.

One of the things I was talking about, questions and concerns we need to raise them
and to look at them very quickly, obviously, but not to come up with quick answer
to these problems and concerns. This is a rather complicated situation. I don't
think we have quick answers to give in any of these particular areas.

Point of fact, we've been talking about water contamination. This is a highly
complicated issue, but let's take a look at a couple of things. One of the things
that Peter Wilford mentioned were the RAE Canberra flight tests. Canberra aircraft
going through different altitudes and through some 172,000 feet going from a cold
environment into a warm and even hot environment and vice versa; there was
absolutely no water contamination nor water encountered and that's an actual test.
We'd like to point out that AMK modified fuel with FM-9, has actually increased the
water solubility. Currently you have water actually settled out from your fuel and
at the end of a particular period, you'll go to the water separator in the aircraft
to take the water out. We can imagine a scenario where the water is soluble to
such a degree that you won't have any water in the separator at all. So you won't
ever have a problem with water. So it's not that water in itself is a difficulty.
As a matter of fact, you're increasing the solubility of water in AMK modified
fuel.

I think the question that we have to look at is how this water is introduced; is it
introduced in tremendous quantities because of fuel quality difficulties? That's
an entirely different issue. We're talking about good housekeeping points and
introducing fuel of good quality. Then, I know the problem is certainly signif-
icantly less if there's any at all.

This is not intended to rebut or criticize anybody, but there are a great many
concerns that are raised and I think justifiably. We need to look at these, but we
also need not be too alarmed about these concerns. That's the interest of the
technical program; and I don't think we want to come up with any quick answers pro
or con at this point.

Discussion: Dr. Parker: Have you actually done a quantitative polymer separation as a function of the amount of water added in these systems and made a phase diagram of this, and determined this in your laboratories?

Mr. Mossel: Dr. Parker, you are above my head.

Dr. Parker: I mean, when you add water to it the glycol basically is acting as a wedge to provide the solubility, and so this is a basic glycol polymer fuel phase diagram and you simply added water to it, a finite amount of water and you can actually calculate then how much polymer you could be expected to participate if you had water added and mixed and that's a very fundamental issue, and I just ask has anyone done it?

Mr. Mossel: Not quantitatively.

Mr. Parker: I think it's needed.

Mr. Hartline: We now can drain water off the bottom of tanks and I gather if the water goes into solution, we can't drain it out and that in itself poses a problem, what happens to the water.

Dr. Reichenbach: We are running short of time, so why don't we move on to our next and last Bill Dukek.

J. A. Parker, NASA Ames Research Center.

As a polymer chemist, I am pleased to be able to participate in this progress review of antimisting kerosene, and it should be understood that any reference I make with regard to crash-fire scenarios and survivability benefits can only be, at best, speculative.

During the period of the war in Southeast Asia, I had the opportunity to participate with the Army group in evaluating the crash-fireworthiness of gel fuels in full-scale crash tests with military fighter aircraft. The failure of this effort to correlate simulation testing to antimisting effectiveness with full-scale tests (failures) has left me skeptical about our understanding of the problem and the benefits to be derived from AMK applications. I don't believe this experience will prejudice the remarks I shall make here today.

I must agree with Mr. Versaw, that to date, the availability and distribution of basic data on the structure properties and performance of FM-9 modified kerosene has been seriously restricted. This fact has made it extremely difficult to make any useful progress in the polymer science aspects of the FM-9 system.

The Chemical Research Projects Office of the NASA, Ames Research Center, is engaged, however, in a number of activities which relate directly to the technical problems of AMK. We have done and are doing considerable work on the fire modeling of large-scale fuel fires, especially plume analyses. This research includes ignition, and fire growth under various flow conditions. Questions such as the ignition and flame spread rate of AMK modified pool fires may be of interest. It is our understanding that antimisting additives are ineffective in JP-4, and do not suppress ignition because there is always a small concentration of low molecular weight flammable, volatile hydrocarbon, that may violate the requirement that the fuel must produce a misted cloud to be ignited and propagated. Perhaps the radiation from hot ignition sources may degrade the fuel to produce low molecular weight hydrocarbons and ignition of a pool of fire. A condition may arise where ignition might not depend on misting characteristics. We are interested in this possible problem. A second consideration of this important effect of low molecular weight volatile hydrocarbon fraction, is the worldwide availability of jet A and the use of wide cut fuels, which can be expected to change the molecular structure and distribution of the fuel component.

Another activity of the Chemical Research Projects Office, addressing these ignition and fuel questions, is our capacity to model and experimentally investigate full-scale pool fires under Navy sponsorship, wherein carrier deck crash fires, fire plumes, and pool fires are defined.

In our group, several fluid mechanic scientists are interested in the non-linear viscoelastic characteristics of polymeric antimisting additives. Several years ago, Dr. Weatherford, from SWRI, made the suggestion that the experimentally determined drag reduction of an AMK modified fuel is a simply measured property, related to the elongational viscosity, a property which is said to characterize the onset of string formation in modified fuels. One of our researchers investigated this relationship and published the results recently in the Journal of the Society of Rheology. This developed simple method provides everyone with a simple technique by which one can easily and conveniently characterize the potential antimisting characteristics of any particular polmer additive polymer. The surprise

is that there are now literally hundreds of off-the-shelf polymers that are candidates for antimisting behavior. This results in a large number of chemical structures that may be useful, some of which are simply viscoelastic like poly-isobutylenes and some which fall into the category of polymers for which the fuel is a theta solvent. They are all drag reducers, although they effect anti-misting by somewhat different mechanisms.

In addition to this data base of structure-property relationships, we now have seen, thanks to ICI's first slide, a list of key properties. We are not screening the hundred or so candidates, in terms of drag reduction efficiency, molecular weight, and molecular weight distribution which one hopes may be related to these key properties. Certainly, we are talking about some "miserable" molecular weight problems, i.e., multiple solvents, difficult solubility, molecular weights in the range of $10^6 - 10^7$ and molecules sensitive to mechanical fracture during manip-ulation. It is not so much a question of number of average molecular weight changes but changes introduced in molecular weight distribution when these polymers are handled, dissolved, stored, and pumped. I should like to suggest that even after degradation (in addition to radical recombination reactions already mentioned) gellation occuring in upstream filters might be due to solution crystal-lization due to flow alignment of the degraded polymer. There may be no way to degrade your way around these problems with these classes of polymers.

We also have the capability of synthesizing high molecular weight polymers by Zeigler-Natta techniques (anionic techniques) to which linear block grafts can be added to control theta temperature, elongational viscosity, to effect partial solubility at low temperature and at the same time effect a high elongation viscosity. I liken this process to a bunch of loose logs, first floating in the river, but easily collimated into a log jam when sheared or forced through an orifice. This model may be close to the truth.

Finally, one talent that one must have in polymer development is the ability to make reasonable cost projections. (Not necessary cost benefit in terms of aircraft fire safety.) We do it all time time.

We generally do it before we initiate a new contract to secure a new polymer to evaluate its potential use. This is especially necessary in the aircraft business, because every time we propose a material change on an aircraft we have to worry about the overall fuel efficiency on the fleet for the next 10 years. We have cost algorithms that predict what this effect is going to be in the long term. I certainly haven't done this in any final way for the alternatives to FM-9 yet.

I am as concerned about the potential cost of these additives as I am about the potential cost benefits of these materials, especially in terms of those events in which the material is really not effective.

Discussions: Dr. Reichenbach: Just a brief statement on JP-4 fuel, which has a low flashpoint. ICI's FM-9 additive is intended to be an antimisting agent and not a vapor pressure reducer. Therefore, the AMK additive, FM-9 would not work in low flashpoint jet fuels and in gasoline that's used in cars, etc.

Dr. Parker: To be sure. The reason for bringing up the JP-4 question in this discussion was to call attention to the fact that there are perhaps several mechanisms that might become important in the way in which a large scale fire may

propagate.   A mist can be formed and ignited to generate a fireball and this propagation can be interdicted by mist reduction with AMK. But it also could be important in a fuel fire, where ignition of spil'ed fuel in a pool can be ignited by exposure to an energetic radiant source, deg ding the fuel to low molecular weight leading to vapor-like candle burning, and suddenly one has an entirely different mechanism over which the AMK has little control. The only argument I wish to raise is what is the probability of these different mechanisms and how does it affect the benefit of using AMK's?

Mr. W.G. Dukek, Exxon Research and Engineering

The petroleum industry has always been interested in safety fuel for aviation beginning with the attempt about 40 years ago to develop safer aviation gasoline. We've enforced low volatility kerosene as a safer fuel for civil aviation than wide-cut JP4 and petroleum research did participate in the development of gels emulsions and viscoelastic additives for military fuel. This new approach of antimisting kerosene deserves strong support, provided its use, of course, doesn't jeopardize the integrity of aircraft systems directly or indirectly. Unlike other safety fuels, however, at this stage, it appears to threaten the conventional ground handling systems that are engineered to deliver clean and dry fuel into aircraft. There is simply no justification for expecting future aircraft to digest water and dirt simply because the fuel contains antimisting additive. However, conventional ground systems could be modified if this becomes the only way to handle AMK. For example, if filtration had to be discarded as a technique for water and dirt removal, and that is our standard method, alternatives need to be explored.

There are systems that have been investigated in the past, for example, electrical coalesence, vapor space drying centrifugation, or perhaps the answer would be a closed sanitary system after quality control checks had been made on a tank of AMK fuel. But let us not deceive ourselves. AMK fuel represents a second and separate system on almost all airports. General aviation, particularly corporate and business jets, will continue to need conventional jet A and, of course, a change-over of the civil fleet would really take many years. The capital investments required for a new fuel handling system are really quite high. The cost, there-fore, of modifying today's ground systems for the safety fuel has really got to add to the cost of the additive.

Now, if the current polymer or an alternative polymer can't be added in at the refinery and survive the distribution and handling system, then success of the entire concept as we've heard, hinges on a workable additive blending system and quality control system near the point of use. That could be the supplier's terminal, an airport tank farm, or the airline's fueling cart. It could also be the dealer at a small airport who must become a blender to handle this strange material. It really is a formidable challenge.

But let's suggest here, that there is a very important long range incentive from the standpoint of fuel availability in this antimisting concept. Every forward study shows a growing demand for distillates at the expense of gasoline. The heavy naptha that will no longer be needed in the gasoline pool could be blended into kerosene to lower its flashpoint by say 5° or 10° with significant availability benefits and improved product quality.

If the antimisting additive made reduced flash kerosene as safe in the crash-fire environment as it makes jet A, a very important safety obstacle to availability would be overcome. Thank you.

GENERAL DISCUSSIONS

Mr. Taylor: Frank Taylor, Cranfield.

I think it's a fairly general comment that accidents where antimisting fuels are going to be relevant are very, very rare; one in a million, one in 10 million, perhaps. If they do happen that infrequently, then this additive that works perhaps 9 times out of 10, 99 times out of 100, is maybe good enough. At the same time, of course, this might cause a crash, perhaps not more than once in 10 million flights, maybe a bit better than that, but you can put numbers to it, but that conflict, that difference of numbers, I think gives a good feeling for the relevant — relative difference in difficulty of achieving what we want to achieve and perhaps in the money we need to spend as well — many orders of magnitude difference between the two.

Whereas, only 4 or 5 years ago people were saying that there was no difference between jet B and jet A because there was always this all enveloping mist with Jet A, analysis of statistics have shown that there is a significant improvement with jet A. Now, exactly the same sort of test setup is being used to sort out what is necessary for antimisting kerosene, an all-enveloping mist. I don't think that happens often enough to be the criterion. I think we could accept something less. I think we're inventing difficulties for ourselves by going for this 120-140 knot business with lots of ignition sources, lots of holes in the tanks, forgetting that if you have lots of holes in the tanks, you'll have lots of bits of things going through the fuselage as well and killing people. I think we're making it too difficult and I think we could kill the whole program by making it too difficult. I think we're trying to run before we can walk, after all we haven't yet found the differences of jet B and we're still considering reduction in flashpoint of jet A, yet, we are trying to go whole hog with antimsting kerosene. It's not consistent.

Dr. Parker: In the use of powdered fire extinguishing agents, one of the techniques is very interesting; that you can actually carry these on an aircraft and activate them to proceed from a passive state to a very active state. When impact occurred, AMK carried in the wall of a tank, just as a hypothesis, mixing could occur and as a consequence the perpetual problem of logistics support would be solved. I offer that as an idea. Maybe someone might think of a way that might be accomplished.

Mr. Versaw: I would like to comment on that. If an additive can be instantly disseminated throughout the fuel to make it effective, then we haven't got any problems blending anyway. We can put it all in the fuel. It will be instantly equilibrated and ready to go. So I think when you've got that, we've got most of these other problems licked.

CONCLUSION OF MEETING

Mr. Westfield: The only thing I would like to add to conclude this meeting, is to thank you for being here. More turned out than we expected. One thing I want to encourage you to do — and I really mean this — is criticize what we do. Critize us and make sure we hear what you're saying because that's the only way you're going to get what you want. If you leave us alone, we might do what you don't want; so keep talking to us.

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